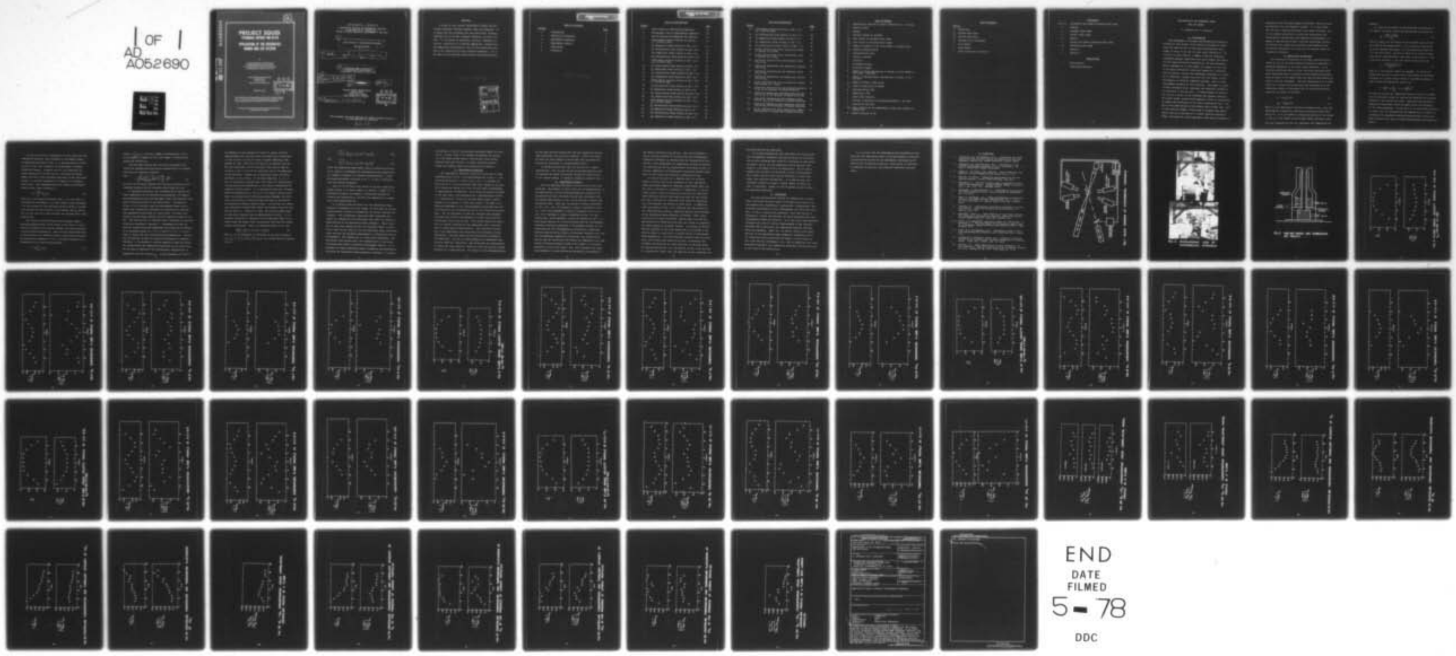
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APPLICATION OF THE INTEGRATED RAMAN AND LDV SYSTEM.(U)
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PROJECT SQUID

TECHNICAL REPORT PIB-35-PU

APPLICATION OF THE INTEGRATED RAMAN AND LDV SYSTEM

by

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FEBRUARY 1978

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PROJECT SQUID

A COOPERATIVE PROGRAM OF FUNDAMENTAL RESEARCH
AS RELATED TO JET PROPULSION
OFFICE OF NAVAL RESEARCH, DEPARTMENT OF THE NAVY

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APPLICATION OF THE INTEGRATED RAMAN AND LDV SYSTEM.

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by

(10) S. Lederman and A. Celentano
Aerodynamics Laboratories
Polytechnic Institute of New York

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Abstract

A series of test results concerning a coaxial jet and coaxial turbulent diffusion methane flame are presented. It is shown that the integrated LDV and pulsed Raman technique represent one of the most complete diagnostic systems available. It is capable of providing, velocity, turbulence intensity, concentration of species, temperature, concentration and temperature fluctuation, as well as the correlation parameters for chemically reacting turbulent phenomena. All of the above can be obtained simultaneously and nonintrusively.

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List of Symbols

C	Experimental Constant or Specie Concentration - See Text
c	Speed of Light
E	Energy
e	Electron Charge in Coulombs
$\bar{e}_i$	Unit Vector of Incident Laser Light
$\bar{e}_{sc}$	Unit Vector of Scattered Laser Light
f_i	Number of Samples of the Total Number of Observations
f_D	Doppler Frequency Shift
G	Photomultiplier Gain
h	Planck's Constant
I	Intensity
k	Boltzmann Constant
ℓ	Scattering Length
N	Number of Scattering Species in Volume or Total Number of Data Point - See Text
n	Number of Photoelectrons Contributing to Signal or Σf_i - See Text
n_i	Number of Times i Term occurs
n_o	Index of Refraction of Medium
R	Photomultiplier Load
T	Temperature (^{o}K)
t	Laser Pulse Duration
V	Voltage or Velocity of Scattering Particles - See Text
u	Velocity of the Flow
X/D	Axial Location in Jet Normalized to Inner Jet Diameter of Coaxial Jet
Z	Radial Location in Jet

List of Symbols

Cont'd

η Efficiency

η_g Quantum Efficiency

η_o Optical Efficiency

λ_o Incident Laser Wavelength

ν Wave Number

Ω Solid Angle

σ Raman Scattering Crossection

Subscripts

AS or A	Antistokes Line Raman Scattering Laser Light
g	Quantum
i	Incident Laser Light
o	Initial Laser Light
p	Photon
s	Stokes Line Raman Scattering Laser Light
sc	Scattered Laser Light
α	Species α
β	Species β

Superscripts

$\bar{\ }$	Mean Quantity
$'$	Fluctuating Quantity

APPLICATION OF THE INTEGRATED RAMAN

AND LDV SYSTEM

S. Lederman and A. Celentano

1. Introduction

The development of reliable and nonintrusive diagnostic methods for flow fields, under adverse environmental conditions has been the aim of continuing investigations for a number of years in our own and many other laboratories. As a result of these efforts, a number of optical diagnostic techniques emerged, among which the Laser Doppler Velocimeter and the Raman Scattering techniques are the most promising. These techniques as is well known, are capable at this time of providing information concerning temperature, concentration of species, velocity and turbulence intensity in a variety of flowfields, ranging from free jets and flames, inlets and exhausts to internal combustion systems. Most of these developments appeared in the literature. The number of publications concerning these techniques and diagnostic methods is to voluminous to discuss here. It should however be pointed out that as a result of the workshops and symposia sponsored by Project Squid, several books appeared, which are collections of papers and discussions on the above technologies (Ref. 1-4). More recent publications on the subject may be found (Ref. 5-9). In this work an attempt is being made to present some experimental results as obtained on a coaxial turbulent diffusion flame, utilizing the single high power laser pulse technique in

combination with the Laser Doppler Velocimeter, which has been incorporated into the diagnostic system. It is also shown that the short duration high power laser pulse technique, due to its inherent properties of permitting simultaneous and instantaneous concentration and temperature measurements of a number of species, may be able to provide information concerning density and temperature fluctuation and possibly cross-correlation information or in the case of reacting flows the "mixedness" parameter.

2. Theoretical Background

The theoretical background of the Raman scattering techniques as well as the Laser Doppler Velocimeter techniques is presented adequately in the above cited references. It is therefore sufficient here to recall the basic governing equations concerning specie concentration and temperature measurements by means of the Raman effect and velocity measurements by means of the LDV techniques. Thus the concentration of a given specie in a mixture may be obtained from the intensity of the vibrational stokes or antistokes line of the scattered laser energy by the specie of interest:

$$I_S = CI_o N\sigma_S f(T) \tag{1}$$

$$I_{AS} = CI_o N\sigma_A f(T) \tag{2}$$

Where C is an experimental constant including filter, lens and spectrograph transmission efficiency, scattering volume solid angle etc., N is the number of scattering species in the volume, σ_S and σ_A is the stokes and antistokes Raman scattering cross sections respectively and f(T) represents the temperature de-

pendence.

In terms of the number of photoelectrons contributing to the signal, the Raman scattering equation may be written as:

$$n_s = \frac{E_o N\sigma . \ell . \Omega \eta_o \eta_g}{E_p} \tag{3}$$

where E_o and E_p are the energy of the incident laser and the scattered photon respectively, η_o is the optical efficiency, η_g is the quantum efficiency, ℓ is the scattering length and Ω is the solid angle. Written in terms of an output voltage pulse from a photomultiplier tube with a gain G across a load R and pulse duration t, the last equation may be written:

$$V_s = \frac{E_o N\sigma \ell \Omega \eta_o \eta_g G.e.R}{E_p . t} \tag{4}$$

where e is the electron charge in coulombs. To obtain the temperature one may use the ratio of the stokes to antistokes intensity for a given specie, which at equilibrium taking account of the Boltzman factor results in:

$$T = \frac{h\nu c}{k} \left[\ln \frac{I_s}{I_{AS}} + 4 \ln \left(\frac{\nu_o + \nu}{\nu_o - \nu}\right)\right]^{-1} \tag{5}$$

One may also obtain the temperature from the ratios of intensities of rotational lines, or from the hot bands of the resolved Q-branch of the vibrational lines. These and other methods of temperature measurement using the Raman effect are discussed in the cited references. In any case, it is clear from equations 3,4 and 5 that the concentration and temperature of a specie in a flowfield is measurable nonintrusively, and when a high power short duration laser pulse is used, instantaneously and simultaneously.

As far as the LDV is concerned it is well known that the theoretical basis for this technique is the Doppler effect. As indicated previously in Ref. 1, 2 and many others too numerious to list, this technique is now becoming a standard laboratory feature. Assuming that all the conditions for proper operation of the LDV are met, including the proper number and size of the scattering particles in the scattering volume, the velocity measurement is reduced to a frequency measurement. That frequency being the change of the Doppler shifted laser light according to:

$$f_D = \frac{n_o V}{\lambda_o} (\bar{e}_{sc} - \bar{e}_i) \tag{6}$$

where f_D is the Doppler frequency shift, n_o is the index of refraction of the medium, λ_o is the incident laser wavelength, V is the velocity of the scattering particle which is assumed to be moving with the velocity of the medium, and $\bar{e}_{sc}$ and $\bar{e}_i$ are the unit vectors of the scattered and incident laser light respectively.

The velocity signals obtained from frequency signals processed appropriately can be stored in the form of a histogram in the memory of an on-line computer and later processed to yeild desired information. Thus with the usual definition of the velocity in a turbulent flow as consisting of the mean and fluctuating component $u = \bar{u} + u'$, the mean velocity of a 1 dimensional L.D.V. may be obtained from

$$\bar{u} = \frac{1}{n} \sum_{i=1}^{k} f_i u_i \tag{7}$$

where $n = \sum_{i=1}^{k} f_i$ is the total number of observations, and f_i is the number of samples of the total number of observations having the velocity u_i.

From the mean velocity and the stored individual velocities the standard deviation may be obtained which is nothing less than the turbulent intensity.

Thus

$$\sigma = \left[\frac{n \sum_{i=1}^{k} f_i u_i^2 - \left(\sum_{i=1}^{k} f_i u_i\right)^2}{n(n-1)} \right]^{\frac{1}{2}} = \sqrt{\overline{u'^2}} \qquad (8)$$

The last two equations indicate that the mean velocity and the turbulent intensity may be obtained easily using an L.D.V.

As indicated previously, the concentration of species and their temperature can be obtained instantaneously (~10-15nsec) and simultaneously using the high power short time duration laser pulse technique by means of the Raman Effect. The question arises if it is possible from the instantaneous Raman data to deduce some information concerning the concentration (density) and temperature fluctuation in a flow field? To answer that question one need only consider the data reduction scheme of the LDV. The mean velocity is obtained from a histogram of individual velocities according to equation 7. Proceeding the same way with the concentration and temperature data which may be defined in an analogous manner as $C = \overline{C} + C'$ and $T = \overline{T} + T'$, it is possible to obtain the mean concentration and temperature. Continuing the same way as with the velocity fluctuation or turbulent intensity, it is possible to utilize equation 8 again and obtain the concentration and temperature fluctuation in the given flow. One has only to substitute the instantaneous concentration or temperature for the velocity u_i. In this procedure $\overline{u}$, $\overline{C}$ and $\overline{T}$

are defined as time averages at a point in space, with the understanding that the mean values are taken over a sufficiently long interval of time for them to become completely independent of time. While for the velocity as measured with the LDV this definition of $\overline{u}$ is satisfied, there may be some objections as far as $\overline{C}$ and $\overline{T}$ are concerned, due to the Raman measuring procedure. However on a statistical basis, the above procedure is still valid. It has been shown Ref. 10, 11, 12 that in chemically reacting flows "the effects of concentration fluctuations can be significant to the point of dominating the chemical reaction rates". It is pointed out that for a strongly skewed distribution of C_α and C_β in a two specie reaction case, where the concentration fluctuations become dominant the third order correlations of these distributions must be included in the generalized chemical kinetic model. In the case of a turbulent chemically reacting flow, where the reaction rates are fast and the scale of turbulence is large, the reaction model based on mean value chemistry may be substantially in error. It is therefore necessary in chemically active turbulent flows to include second and higher order correlations involving the concentration fluctuations. These, as defined by Hilst et al, are:

$$\overline{C'_\alpha C'_\beta} = \frac{1}{N} \sum_i n_i \, (C_{\alpha i} - \overline{C}_\alpha) \, (C_{\beta i} - \overline{C}_\beta) \qquad (9)$$

where n_i is the frequency of occurrence of the joint values of $C_{\alpha i}$, $C_{\beta i}$, $N = \sum_i n_i$ and C_α and C_β are the concentration of species α and β.

$$\overline{C_\alpha'^2 C_\beta'} = \frac{1}{N} \sum_i n_i \, (C_{\alpha i} - \overline{C}_\alpha)^2 \, (C_{\beta i} - \overline{C}_\beta) \qquad (10)$$

and

$$\overline{C_\alpha' C_\beta'^2} = \frac{1}{N} \sum n_i \, (C_{\alpha i} - \overline{C}_\alpha) \, (C_{\beta i} - \overline{C}_\beta)^2 \qquad (11)$$

Since the spontaneous Raman Effect used as indicated previously is capable of providing the concentrations and temperatures of a number of species in a mixture simultaneously, a simple processing procedure according to eq. 9, 10 and 11 would provide the desired parameters.

With all of the basic data stored in the data acquisition memory system, it is quite simple to construct a number of correlations of interest for example a correlation between the velocity and concentration, velocity and temperature or temperature and concentration etc.

It is obvious from the above that the spontaneous Raman diagnostic techniques are quite unique, in that they can provide nonintrusively a wealth of information, not easily otherwise obtainable. One's enthusiasm concerning these techniques must however be tempered by the realization that there are limits of applicability of the spontaneous Raman technique. Those limits are in many cases imposed by the low achievable signal to noise ratio, which can be traced to the low equivalent Raman scattering cross sections and attempted measurements in excessively hostile environments. The combination of a very noisy environment, low scattering cross section and a low concentration of the specie of interest may render a particular measurement useless. It is therefore of utmost importance before attempting any measurements utilizing the spontaneous Raman diagnostic technique, to evaluate

the system in terms of the possibly achievable signal to noise ratio. In most cases it is possible to optimize the system, be it by higher energy shorter time duration laser pulses, narrower band pass filters, or higher resolution spectrographs and properly gated data acquisition electronics.

3. Experimental Apparatus

The experimental apparatus utilized in this work is shown diagramatically in Fig. 1 and photographically in Fig. 2. The detailed description is given in Ref. (13). It consists essentially of a 3 joule Q-switched Ruby laser capable of delivering 5 pulses per minute of 20 nsec in half width corresponding to approximately 150 MW/pulse. Four receiving stations focussed at the same point, each equipped with a photomultiplier placed in a thermoelectric cooler, can provide Raman signals corresponding to the species at their focal points. The type of information depending on the interchangeable narrow band pass filters placed in the collimated portion of the collected scattered beam. For the experiment at hand the receivers were equipped with band pass filters corresponding to stokes and antistokes vibrational lines of N_2 and CO_2. This system enabled the apparatus to provide concentration and temperature data concerning both of these species simultaneously. The apparatus included also a one dimensional LDV system which was providing velocity information. Both the Raman and LDV systems were focussed at the same point. The jet or flame mounted on an adjustable base could be moved in 3 directions, thus permitting the determination of radial and axial profiles, while the laser and optical systems remained in a fixed position. The outputs of the photomultipliers

of the Raman and LDV systems were fed into appropriate processing electronics and an on-line computer. After each series of tests the total number of stored data were processed and printed out according to a preprogrammed format.

It should be noted here that the jet was of a coaxial construction. Air, CO_2 and the LDV scattering particles were fed through the center and methane through the outer portion of the coaxial system. A schematic diagram is shown in Fig. 3.

4. Experimental Results

With the apparatus described a series of tests have been conducted. The purpose of these tests was the demonstration of the applicability of the integrated Raman-LDV system and the presentation of some turbulence related data obtainable from the pulsed Raman system, as well as the ability to obtain some correlation data. Thus Fig. 4-8 present a series of profiles at X/D = 4.5. Fig. 9-13 present a series of profiles at X/D = 5.2. Fig. 14-18 represent a series of profiles at X/D = 5.8, Fig. 19-23 represent a series of profiles at X/D = 6.5 and finally Fig. 24-28 represent a series of profiles at X/D = 7.1. Each group consists of a velocity profile and the corresponding turbulent intensity normalized to the maximum velocity, N_2 concentration and the corresponding N_2 fluctuation, temperature profile based on the N_2 stokes to antistokes intensity ratio and the corresponding temperature fluctuation, CO_2 concentration profile and its fluctuation and finally the temperature and temperature fluctuation profile based on the stokes to antistokes intensity of CO_2 in the flame. Fig. 29-30 represent the mixedness parameter or cross-correlation parameter corresponding to

the several profiles of N_2 and CO_2. Fig. 31-35 represent a series of axial profiles of velocity with the corresponding turbulence intensity, N_2 concentration and concentration fluctuation, axial temperature and temperature fluctuation profile CO_2 concentration and CO_2 concentration fluctuation as well as an axial temperature and temperature fluctuation profile based again on the stokes and antistokes intensities of CO_2.

In view of the work of A. Eckbreth Ref. (9) in which doubts are being cast at the usefulness of the spontaneous Raman scattering diagnostic technique, particularly where carbon soot is involved as a byproduct of combustion, it was decided to run a series of qualitative tests on the same flame under identical initial flow conditions with the only difference that a quantity of carbon particles would be introduced. Fig. 36-40 present the results of these tests. A comparison with the results of Fig. 31-35, indicate that the presence of the carbon particles did not completely destroy the usefulness of the spontaneous Raman diagnostic technique. While these tests are by no means conclusive, they do point out that the mere presence of carbon particles does not render the spontaneous Raman diagnostic technique useless. As pointed out by Eckbreth an increase in the laser energy may still provide a sufficient signal to noise ratio to permit the use of spontaneous Raman diagnostics. It is believed that further tests are necessary, particularly some quantitative test, to determine the tolerable concentration of carbon particles in the flow field. As indicated previously, the test results of Fig. 36-40 are only of a qualitative nature since the quantity of the introduced car-

bon particles was not monitored.

It is worth pointing out here that while the velocity and the corresponding turbulence intensity profiles of the several sets of data presented were based on a histogram of 2000 points per point, the N_2, CO_2 and temperature radial profiles were based on a histogram of only 50 points/point, and the corresponding axial profiles on histograms of only 30 points/point. This circumstance by itself may be sufficient to cause some higher then expected fluctuations. It is obvious that for a reasonable statistical sample a higher number of points per point is desirable. Thirty or even 50 points per point cannot be considered sufficient.

5. Conclusion

The work presented here through the combined use of Laser Raman Scattering and Laser Doppler Velocimetry has achieved the long sought after simultaneous, nonintrusive, instantaneous, and pointwise measurements of many thermodynamic and fluid flow variable, as well as correlation parameters. With this wealth of information, further correlations can now be determined and other thermodynamic properties inferred. It is felt that these measuring techniques may lead to a better understanding of the turbulent phenomena and in particular the complicated reacting turbulent fluid flow problems. There are, of course, limits to the applicability of the spontaneous Raman diagnostic techniques such as low scattering cross section and low signal to noise ratios in soot laden hostile environments, etc., but in comparison with other measuring techniques, the information obtainable justifies putting up with some of the difficulties.

It is evident from the experimental data presented in this work that the spontaneous Raman scattering diagnostic technique is particularly suited for the experimental determination of some of the correlation parameters, which may be of importance in modeling of turbulent, and turbulent chemically reacting flows.

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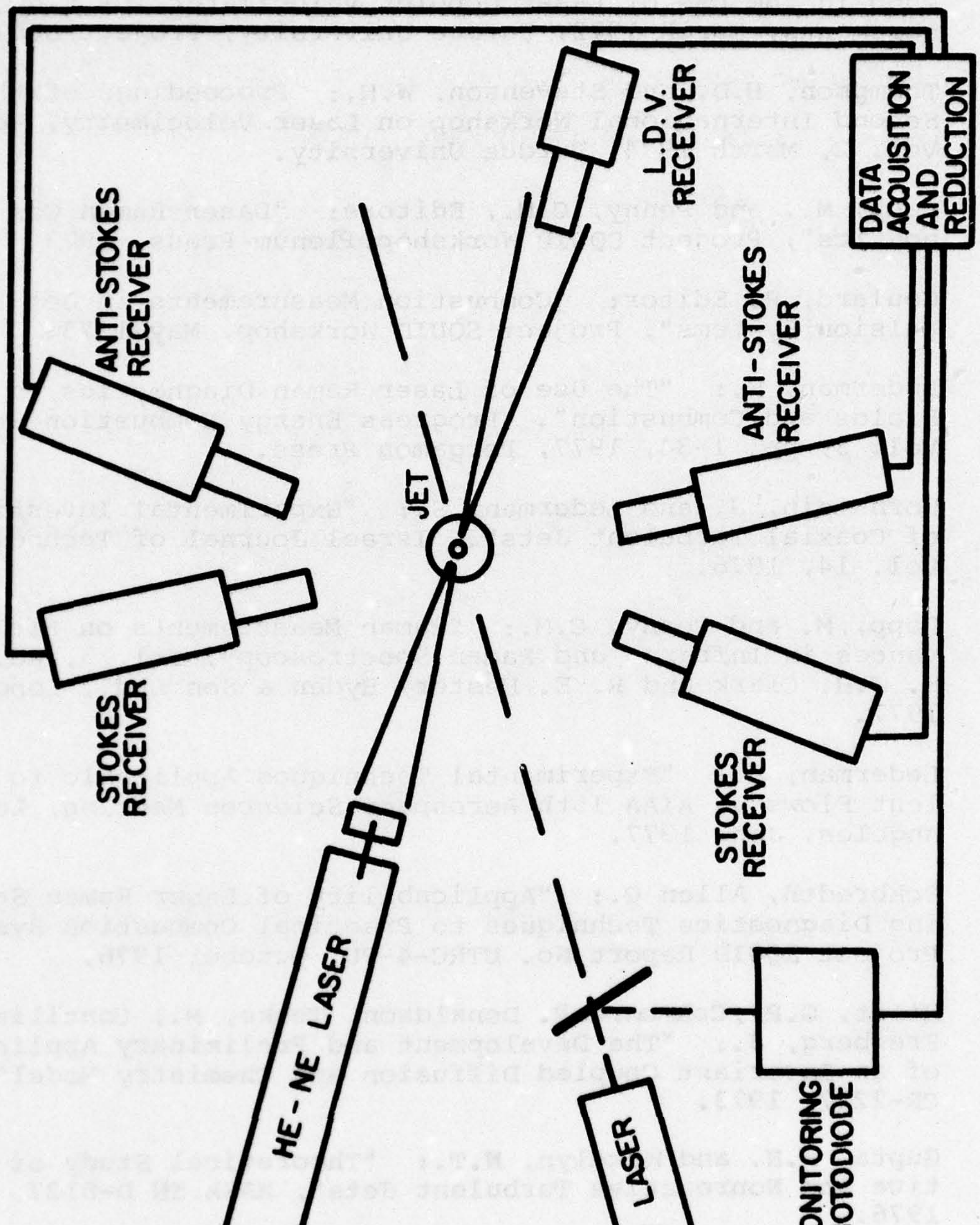


FIG. I BLOCK DIAGRAM OF EXPERIMENTAL APPARATUS



FIG. 2 PHOTOGRAPHIC VIEW OF EXPERIMENTAL APPARATUS

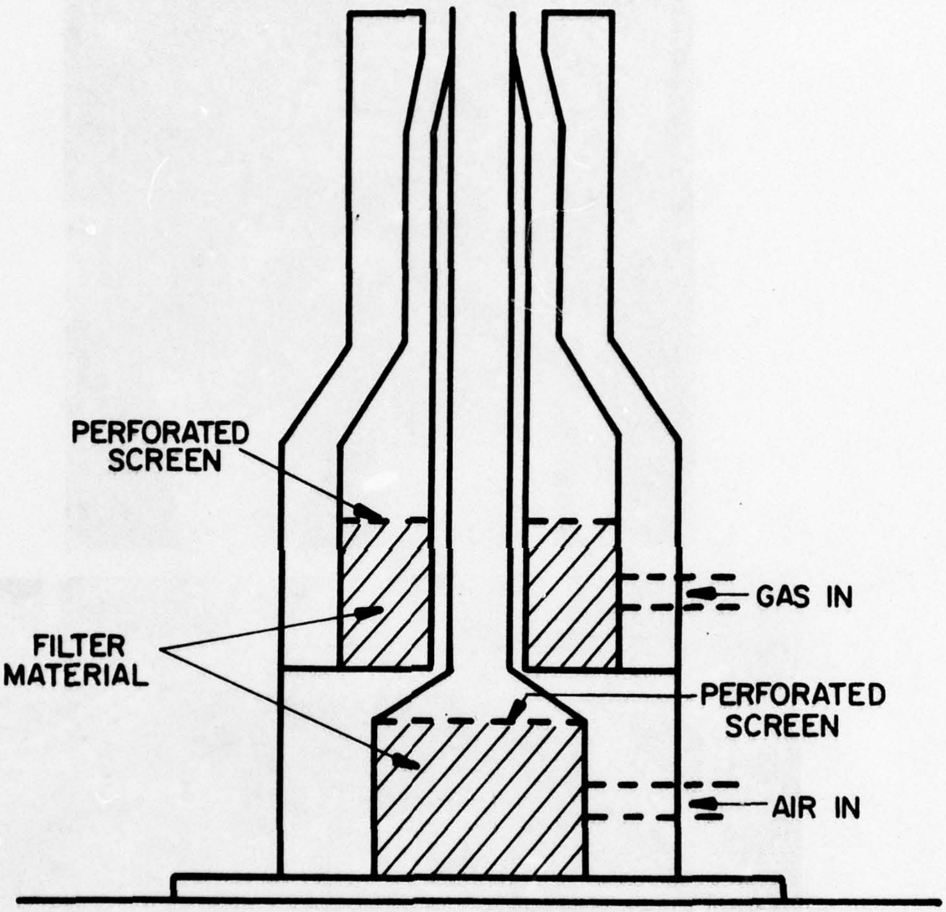


FIG. 3 GAS-AIR MIXING AND COMBUSTION JET FACILITY

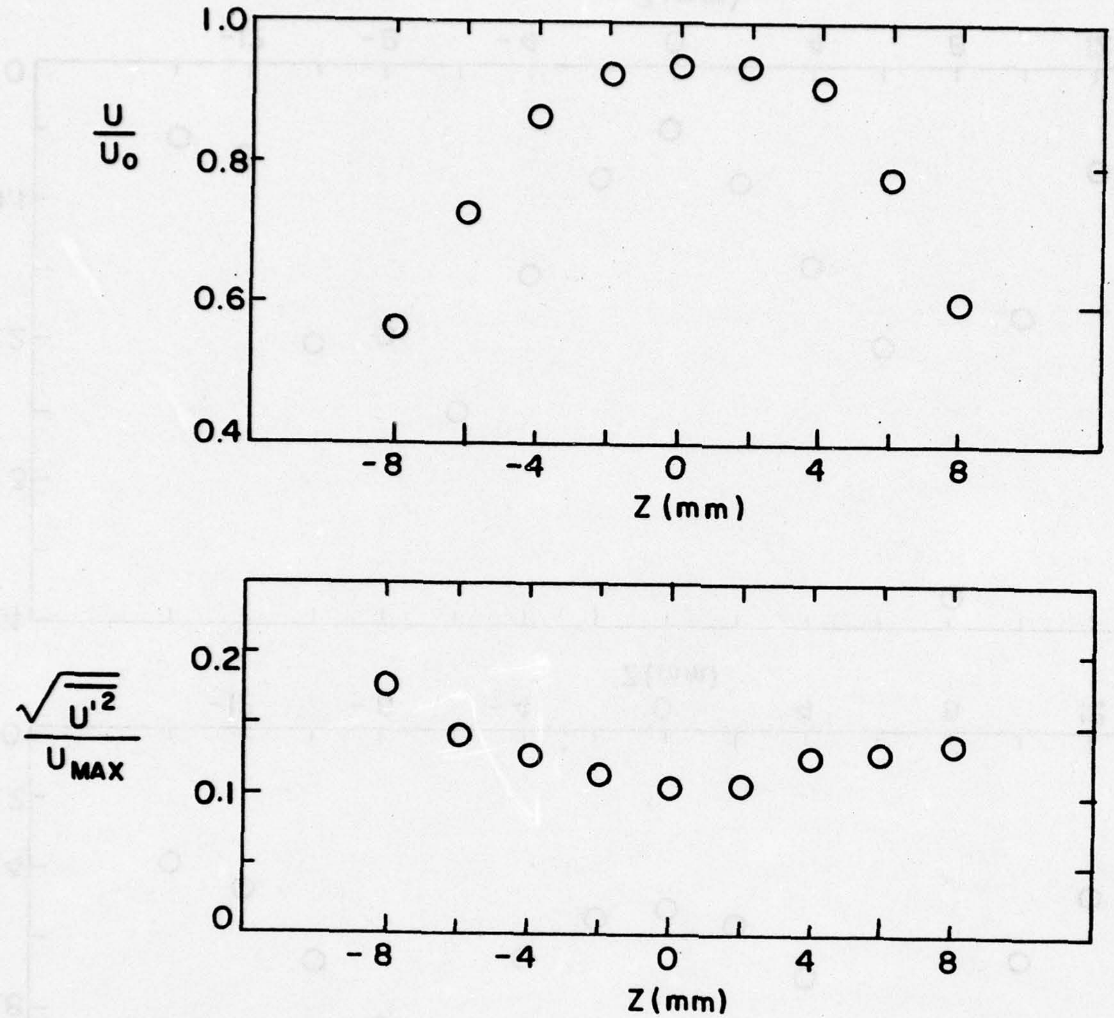


FIG. 4 FLAME RADIAL VELOCITY PROFILE AT X/D = 4.5, U_0 = 44.99 FT/SEC

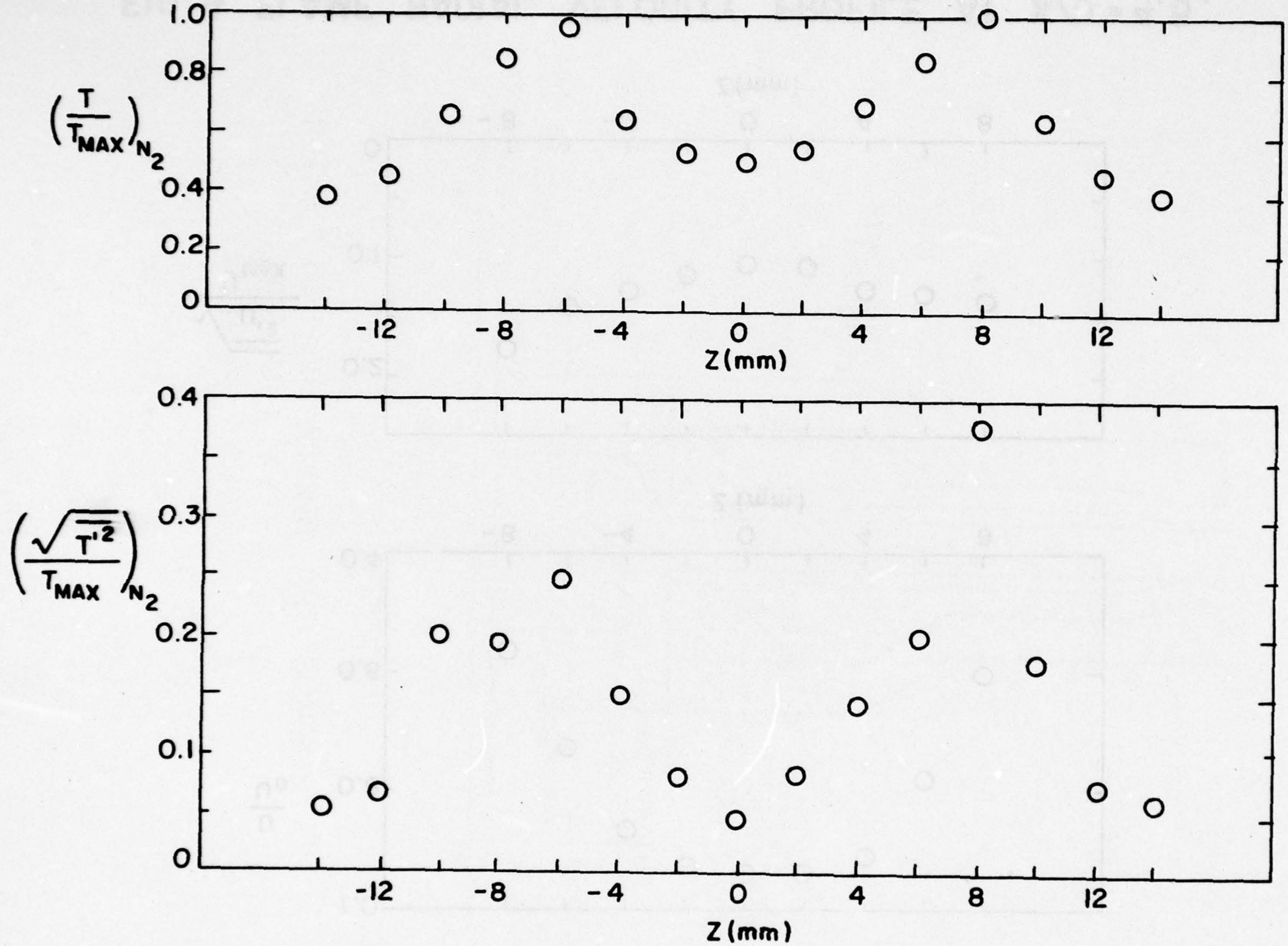


FIG.5 N_2 TEMPERATURE FLAME PROFILE AT X/D = 4.5

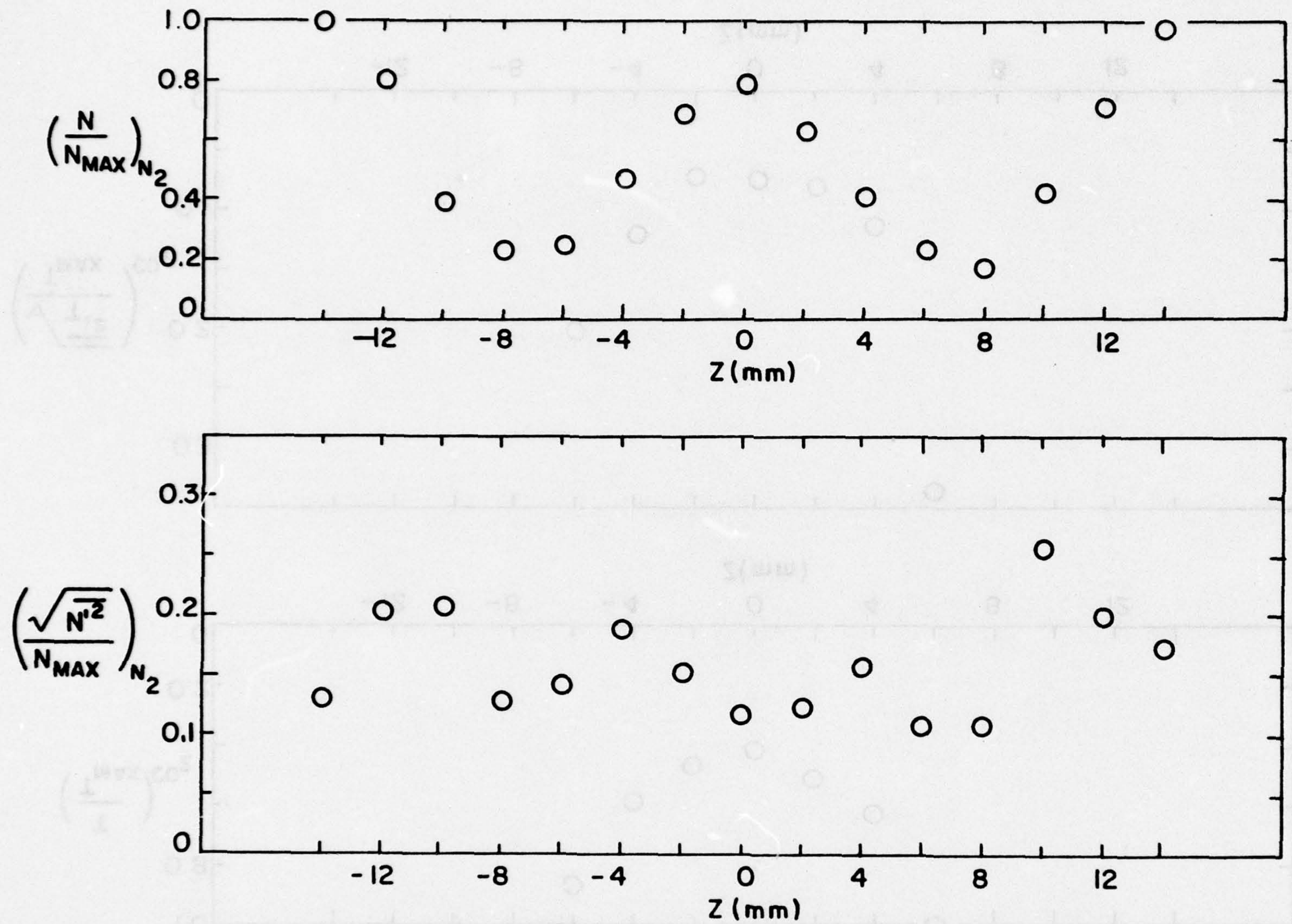


FIG.6 N_2 CONCENTRATION FLAME PROFILE AT X/D =4.5

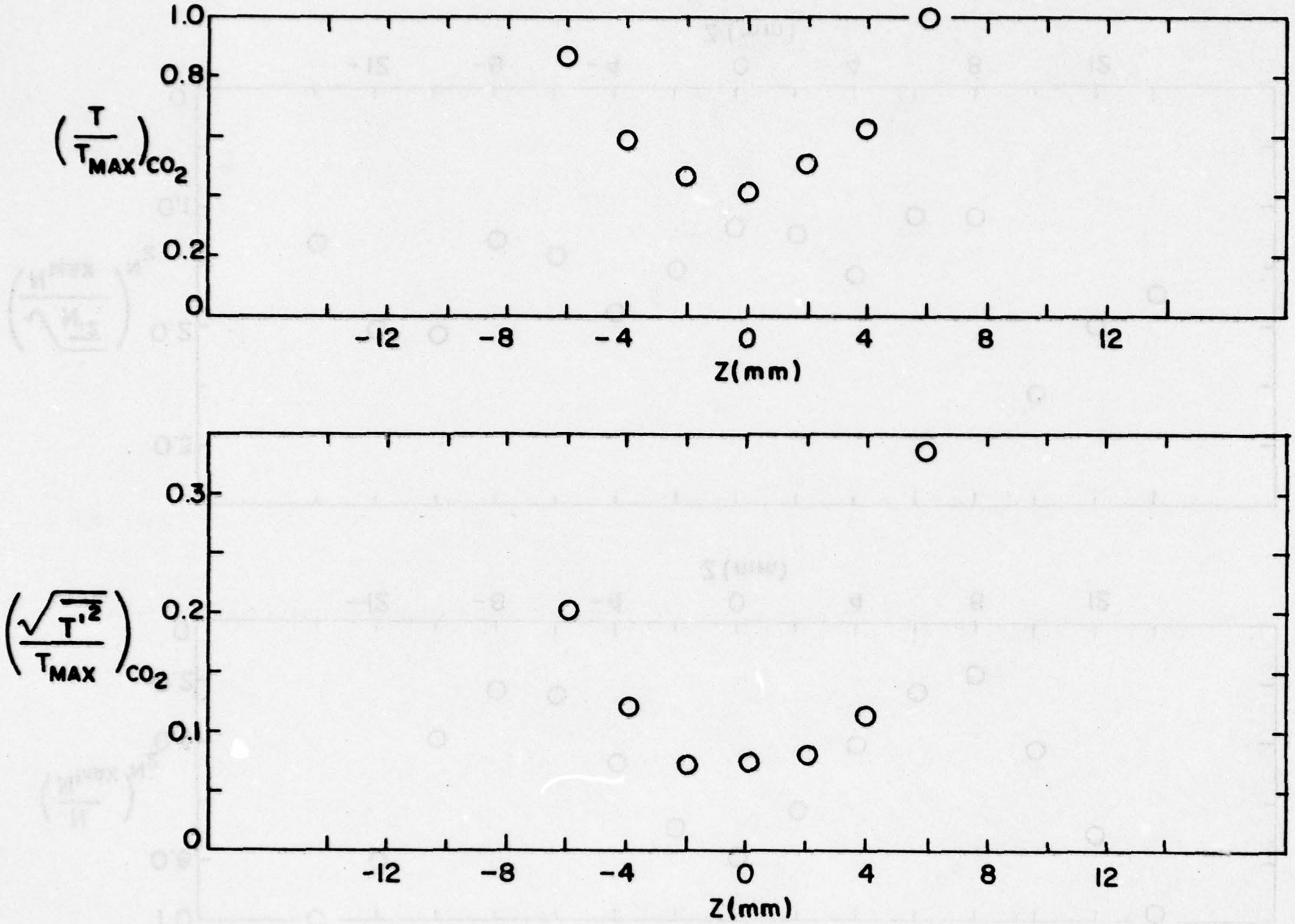


FIG.7 CO_2 TEMPERATURE FLAME PROFILE AT X/D = 4.5

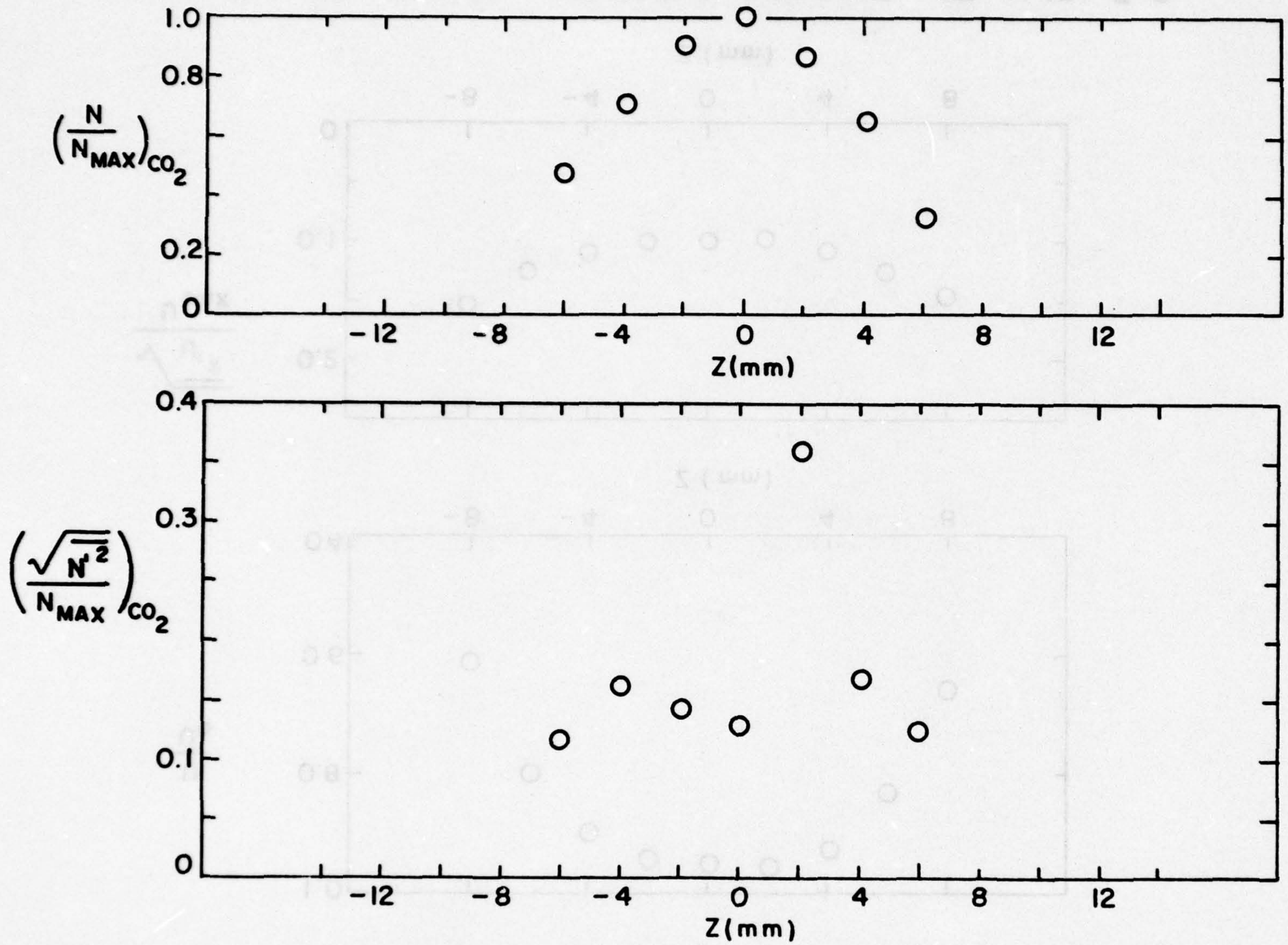


FIG. 8 CO_2 CONCENTRATION FLAME PROFILE AT X/D = 4.5

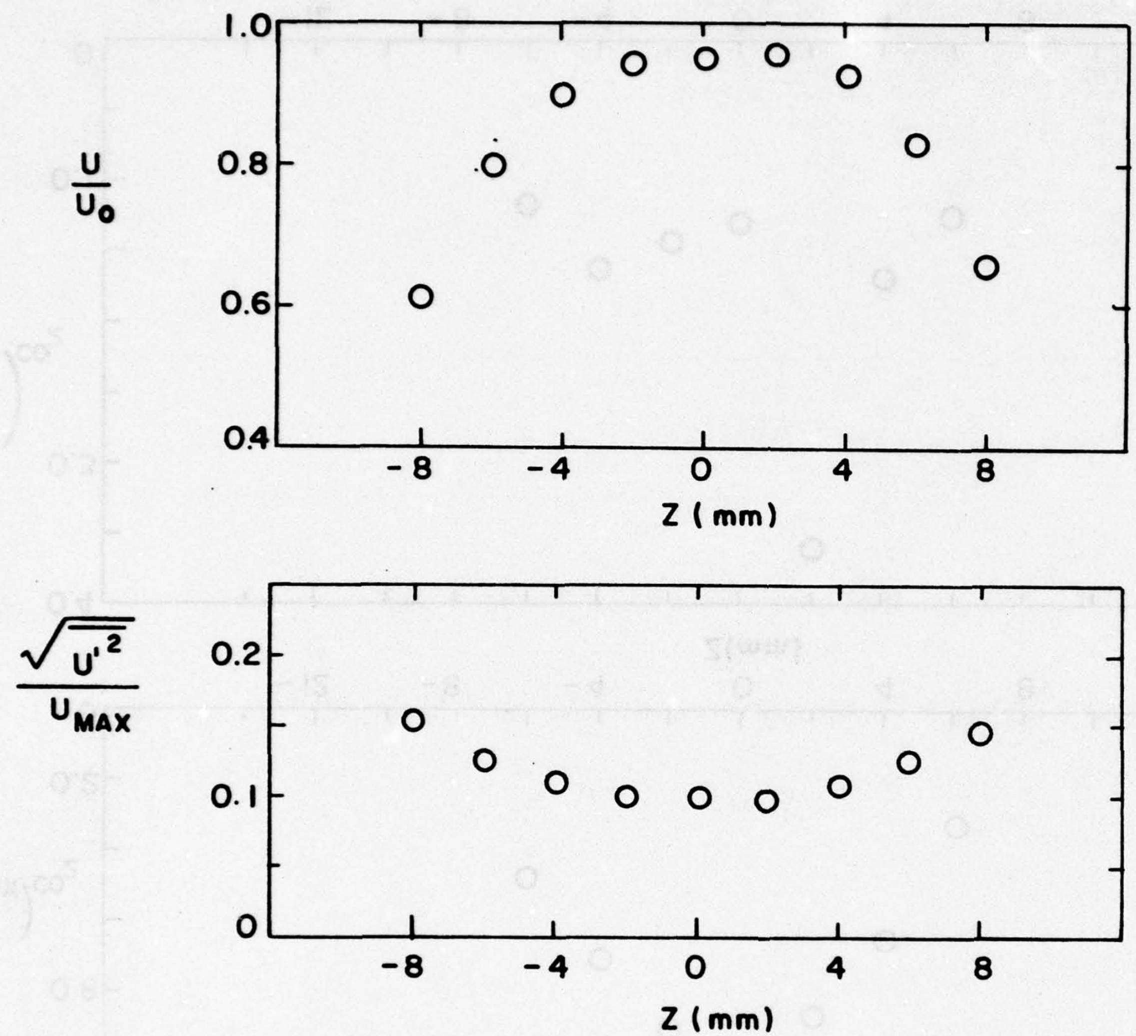


FIG. 9 FLAME RADIAL VELOCITY PROFILE AT X/D = 5.2, U_0 = 44.99 FT/SEC

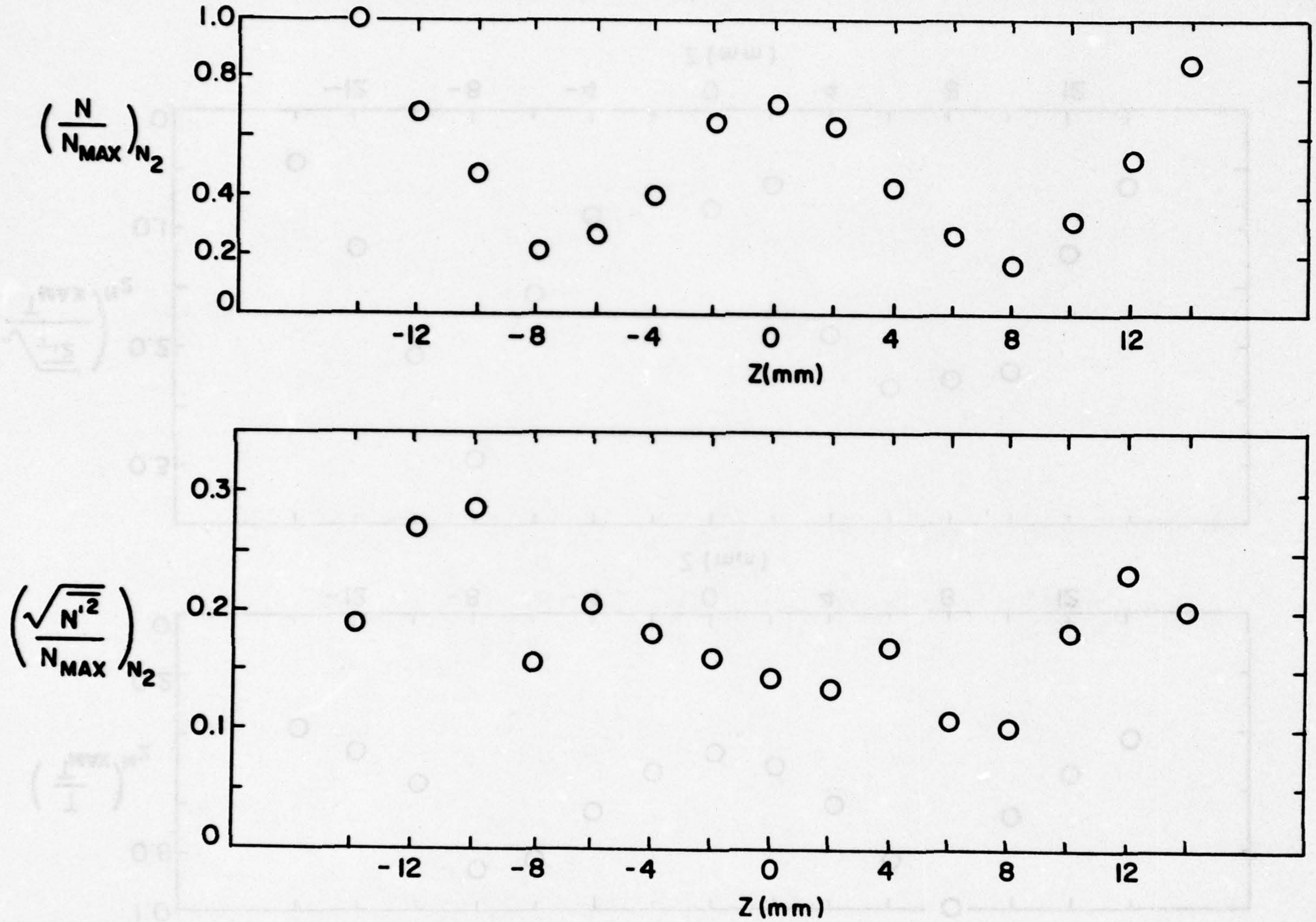


FIG. 10 N_2 CONCENTRATION FLAME PROFILE AT X/D = 5.2

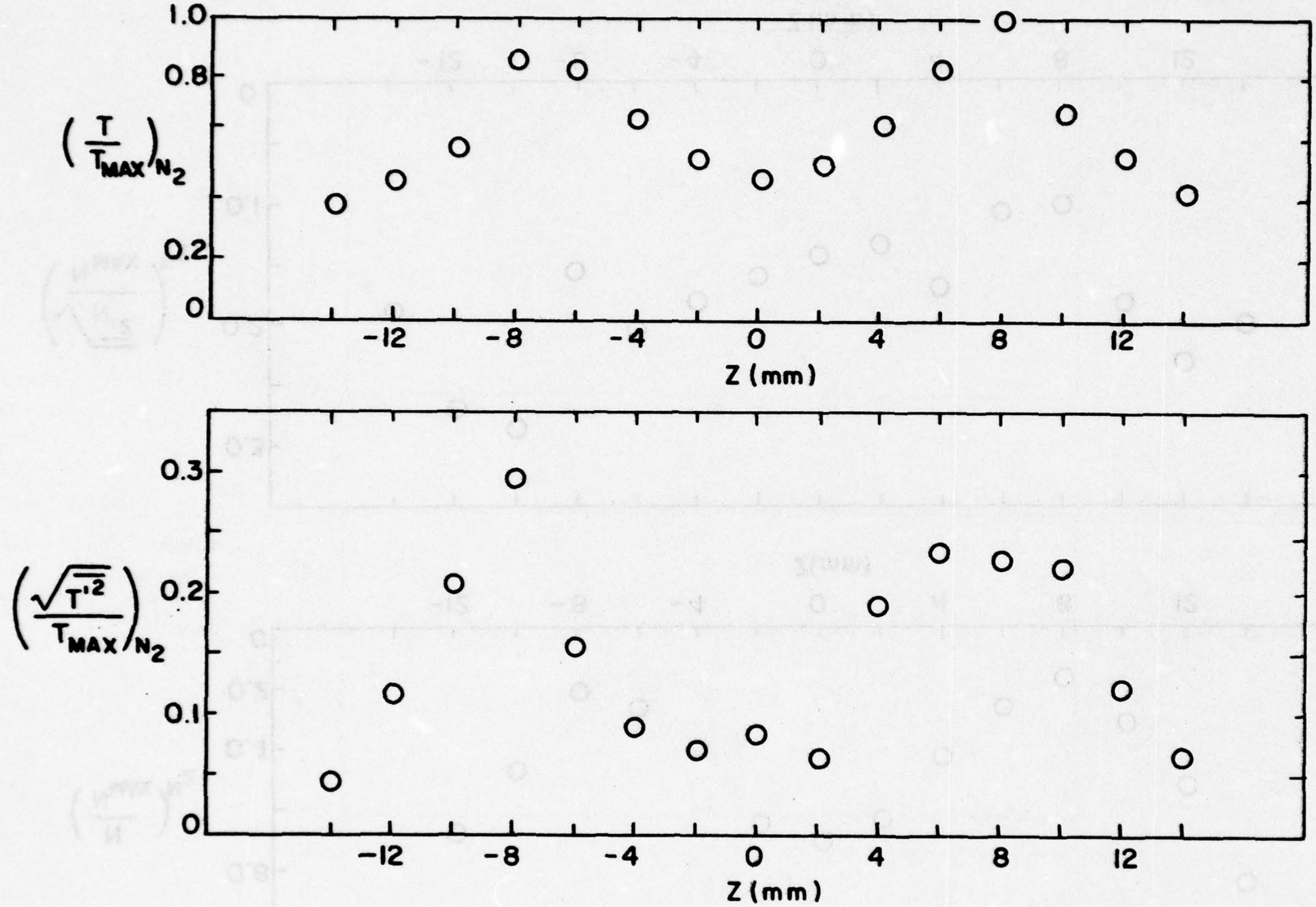


FIG. 11 N_2 TEMPERATURE FLAME PROFILE AT X/D = 5.2

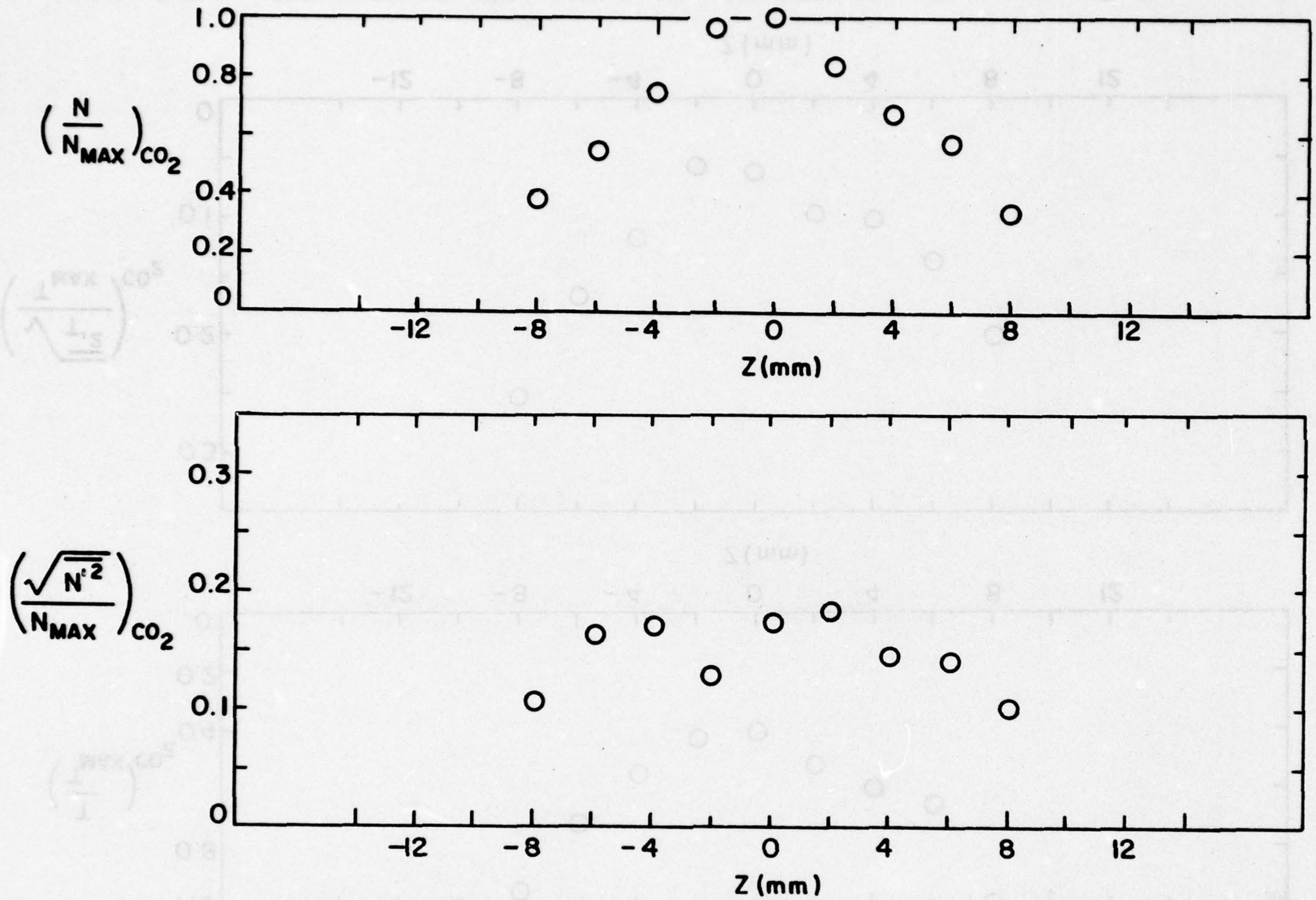


FIG. 12 CO_2 CONCENTRATION FLAME PROFILE AT X/D = 5.2

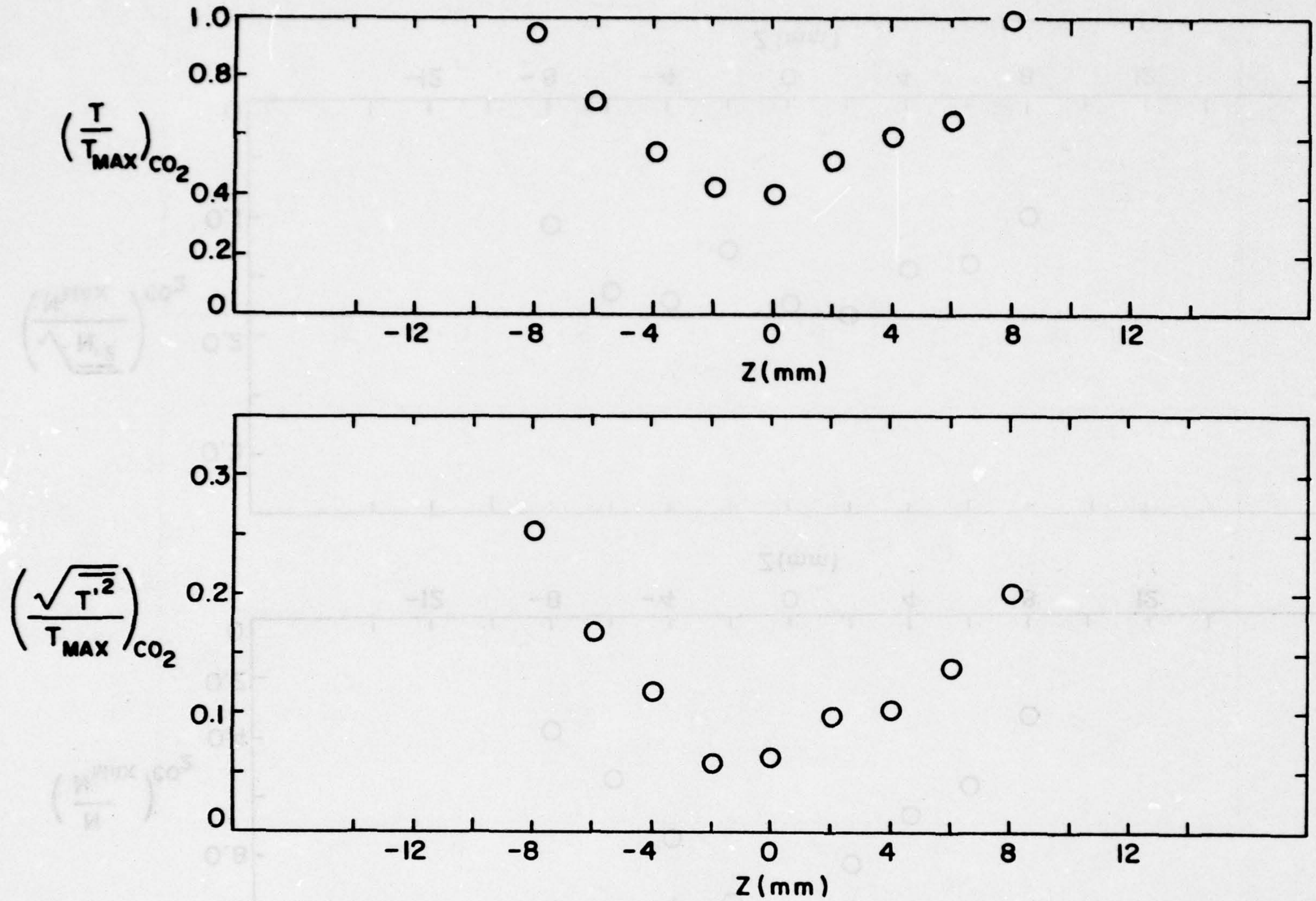


FIG. 13 CO_2 TEMPERATURE FLAME PROFILE AT X/D = 5.2

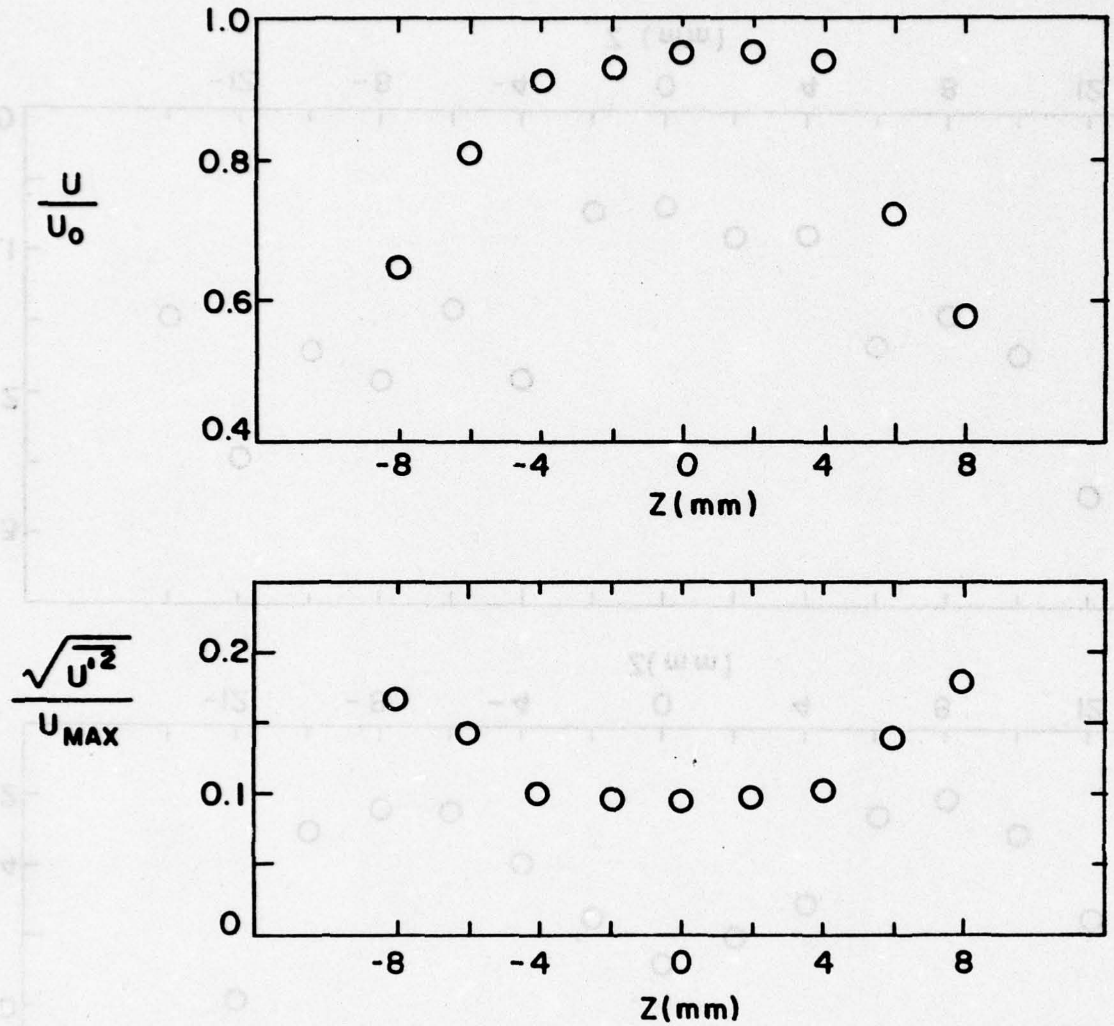


FIG. 14 FLAME RADIAL VELOCITY PROFILE AT X/D = 5.8, U_0 = 44.99 FT/SEC

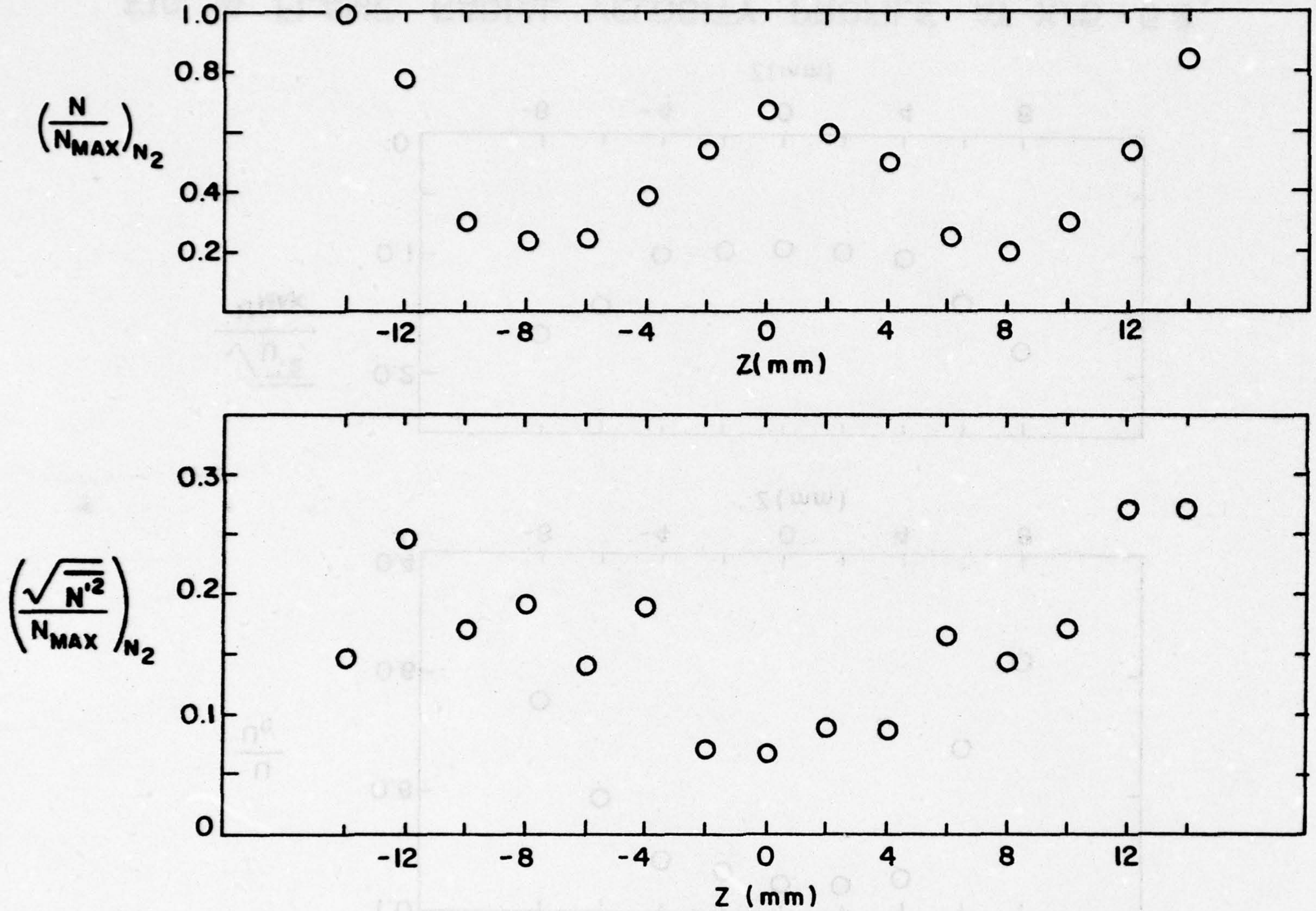


FIG. 15 N_2 CONCENTRATION FLAME PROFILE AT X/D = 5.8

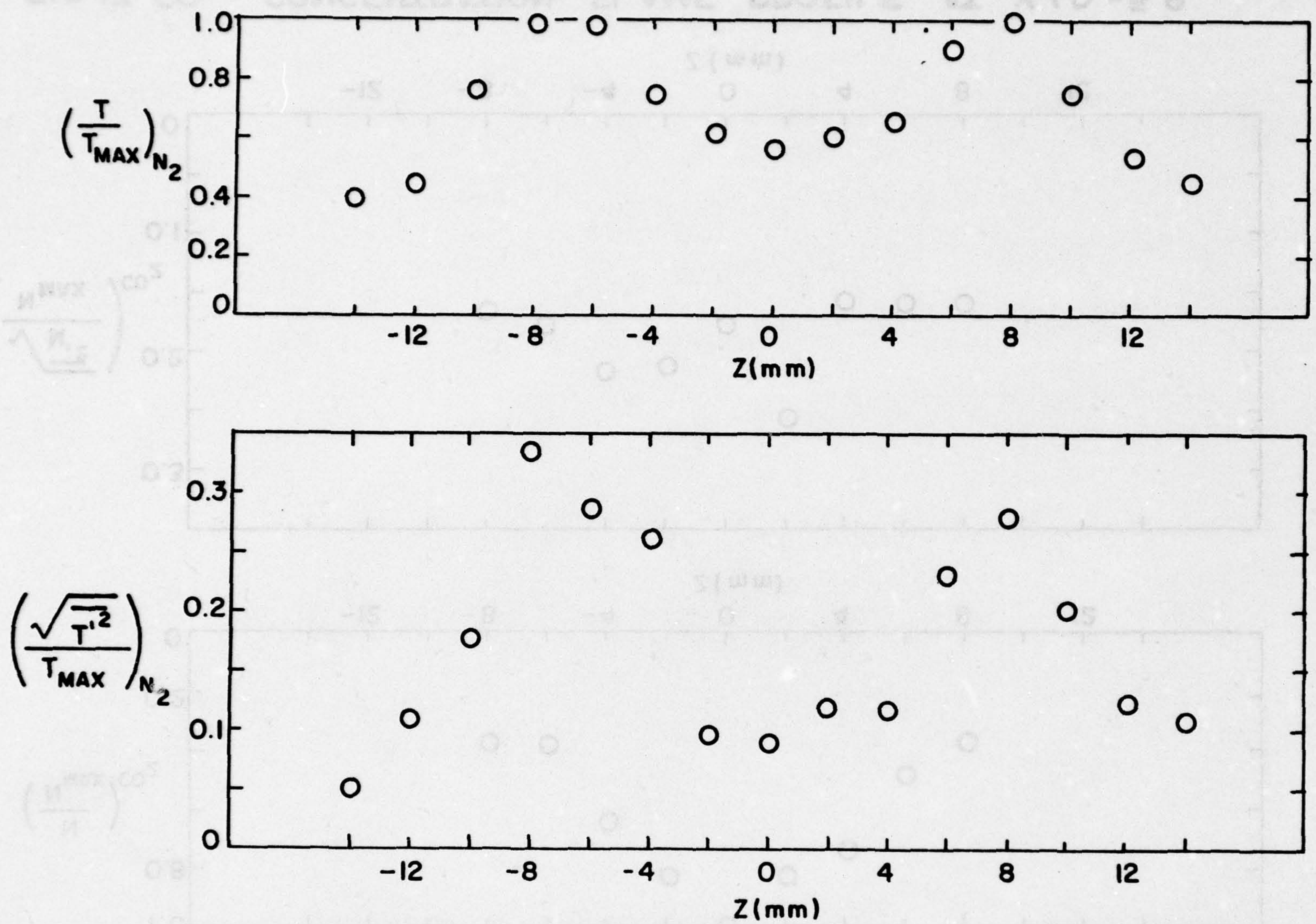


FIG. 16 N_2 TEMPERATURE FLAME PROFILE AT X/D = 5.8

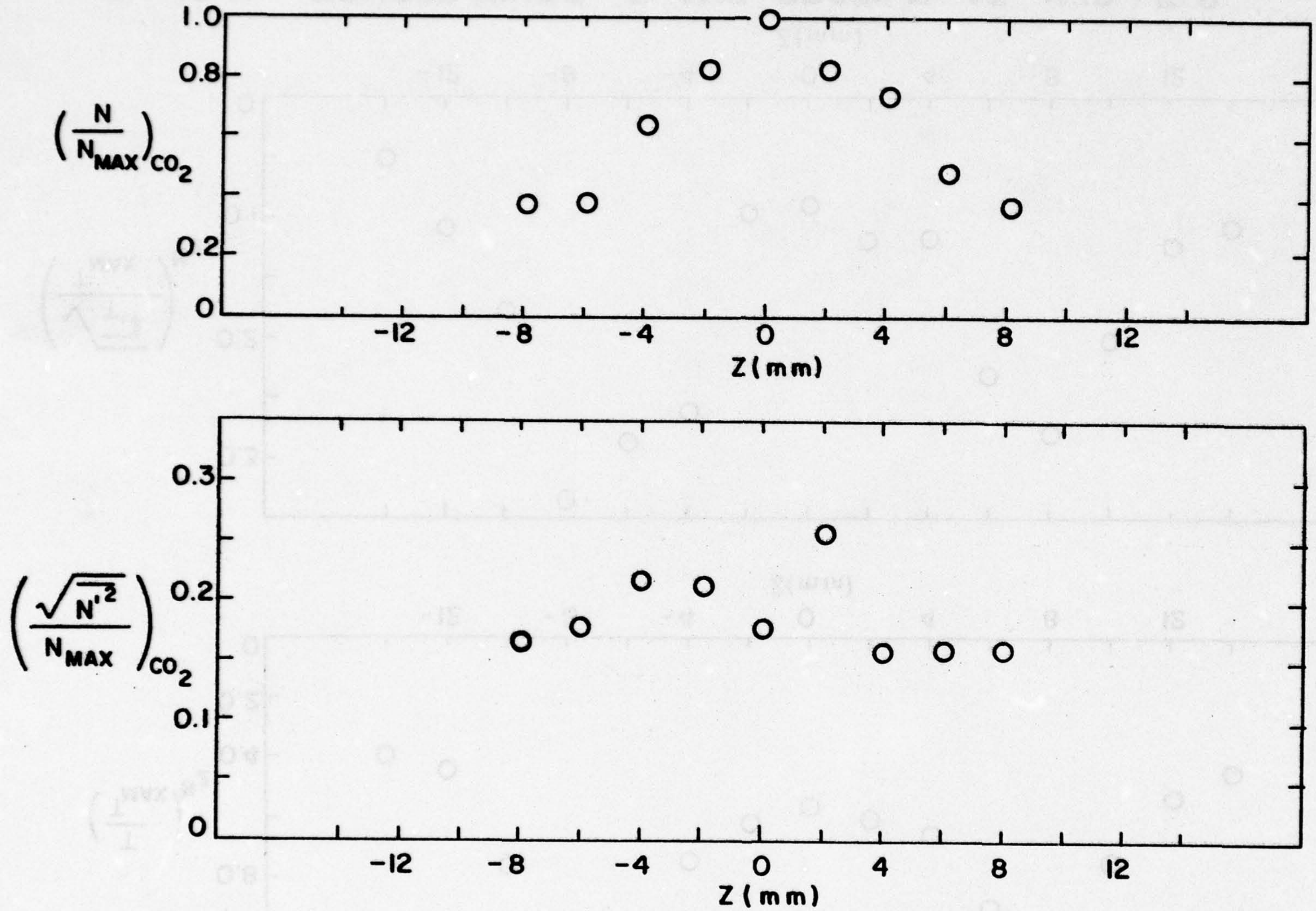


FIG. 17 CO_2 CONCENTRATION FLAME PROFILE AT X / D = 5.8

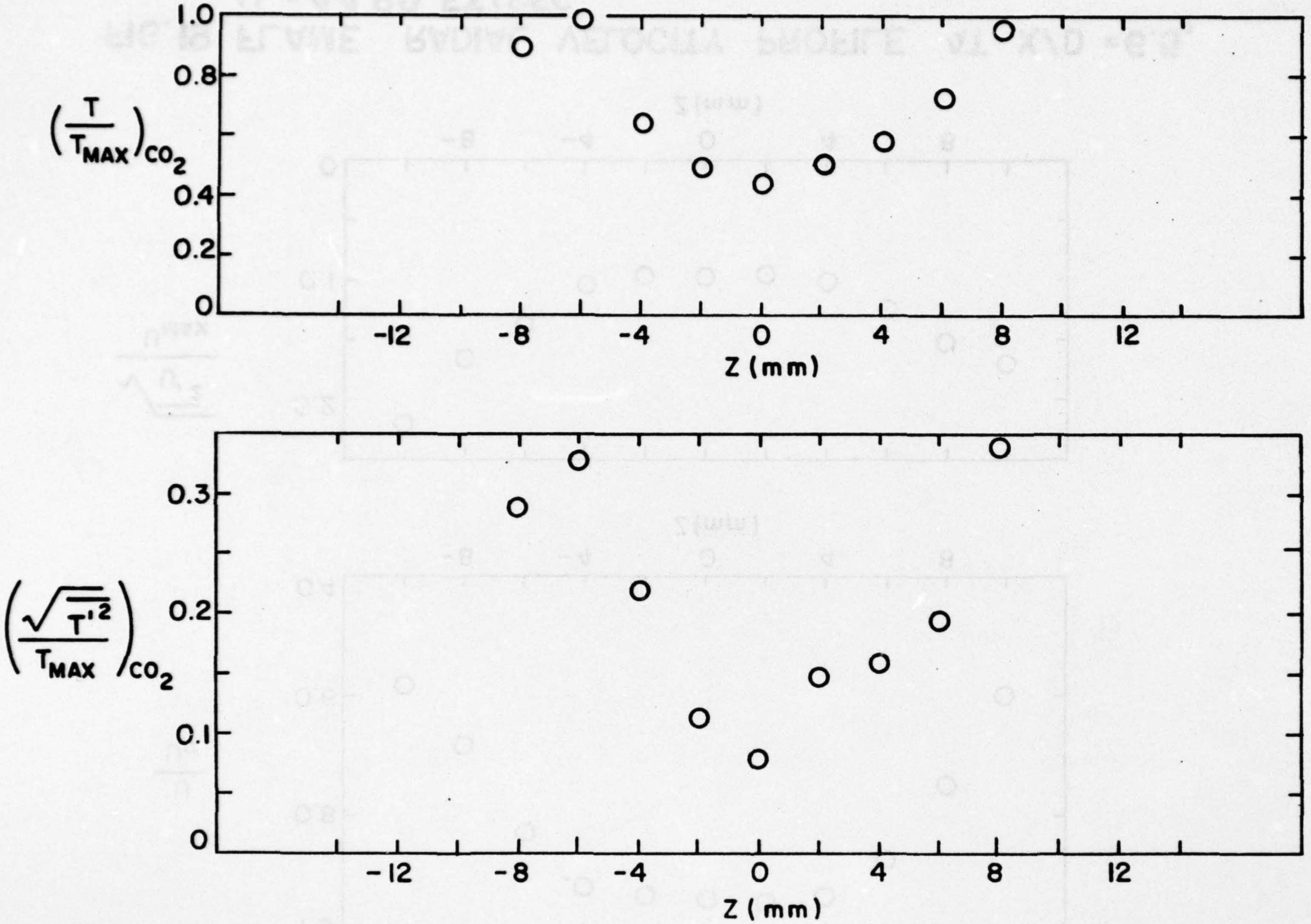


FIG. 18 CO_2 TEMPERATURE FLAME PROFILE AT X/D = 5.8

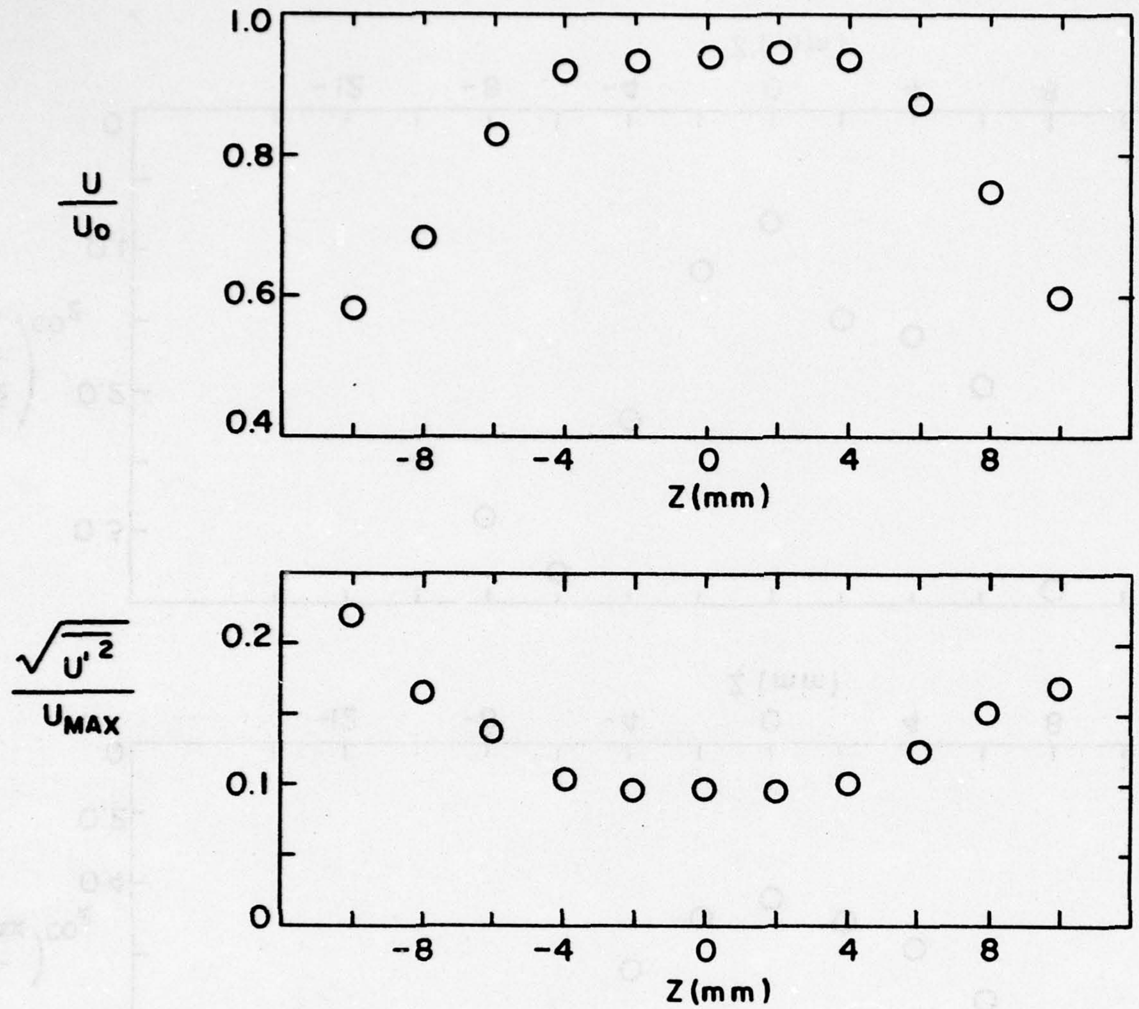


FIG. 19 FLAME RADIAL VELOCITY PROFILE AT X/D = 6.5, U_0 = 44.99 FT/SEC

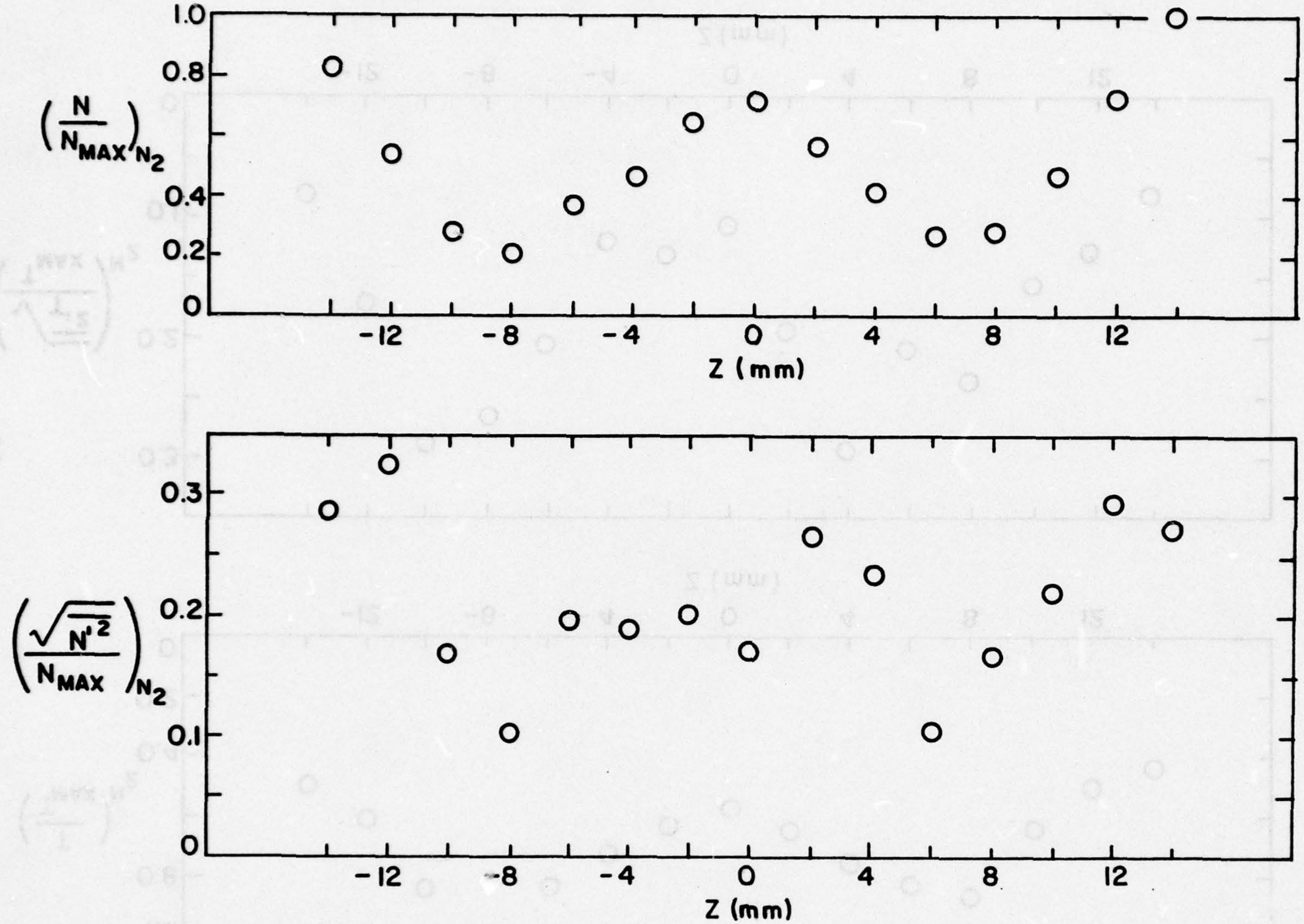


FIG. 20 N_2 CONCENTRATION FLAME PROFILE AT X/D = 6.5

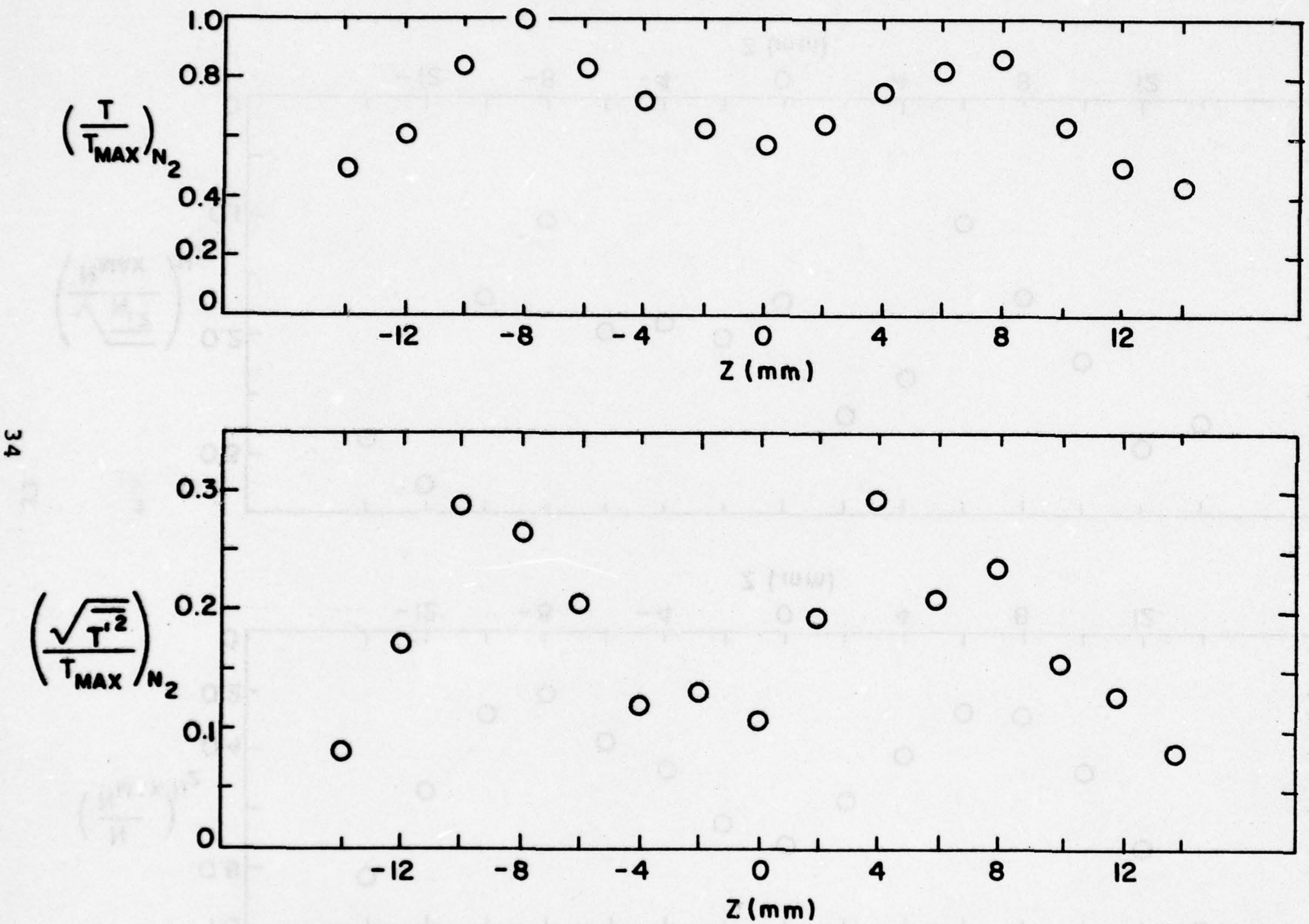


FIG.21 N_2 TEMPERATURE FLAME PROFILE AT X/D = 6.5

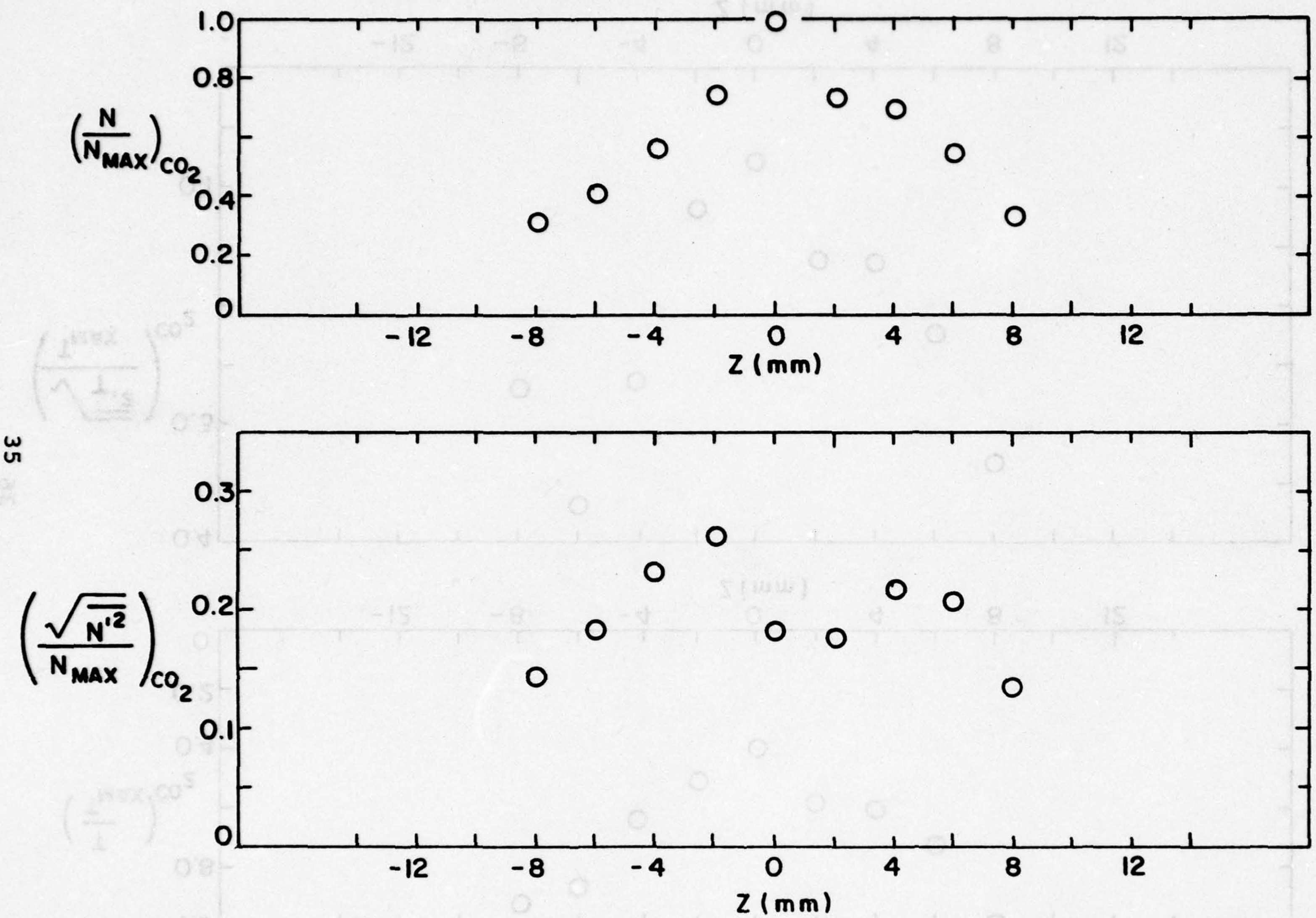


FIG.22 CO_2 CONCENTRATION FLAME PROFILE AT X/D = 6.5

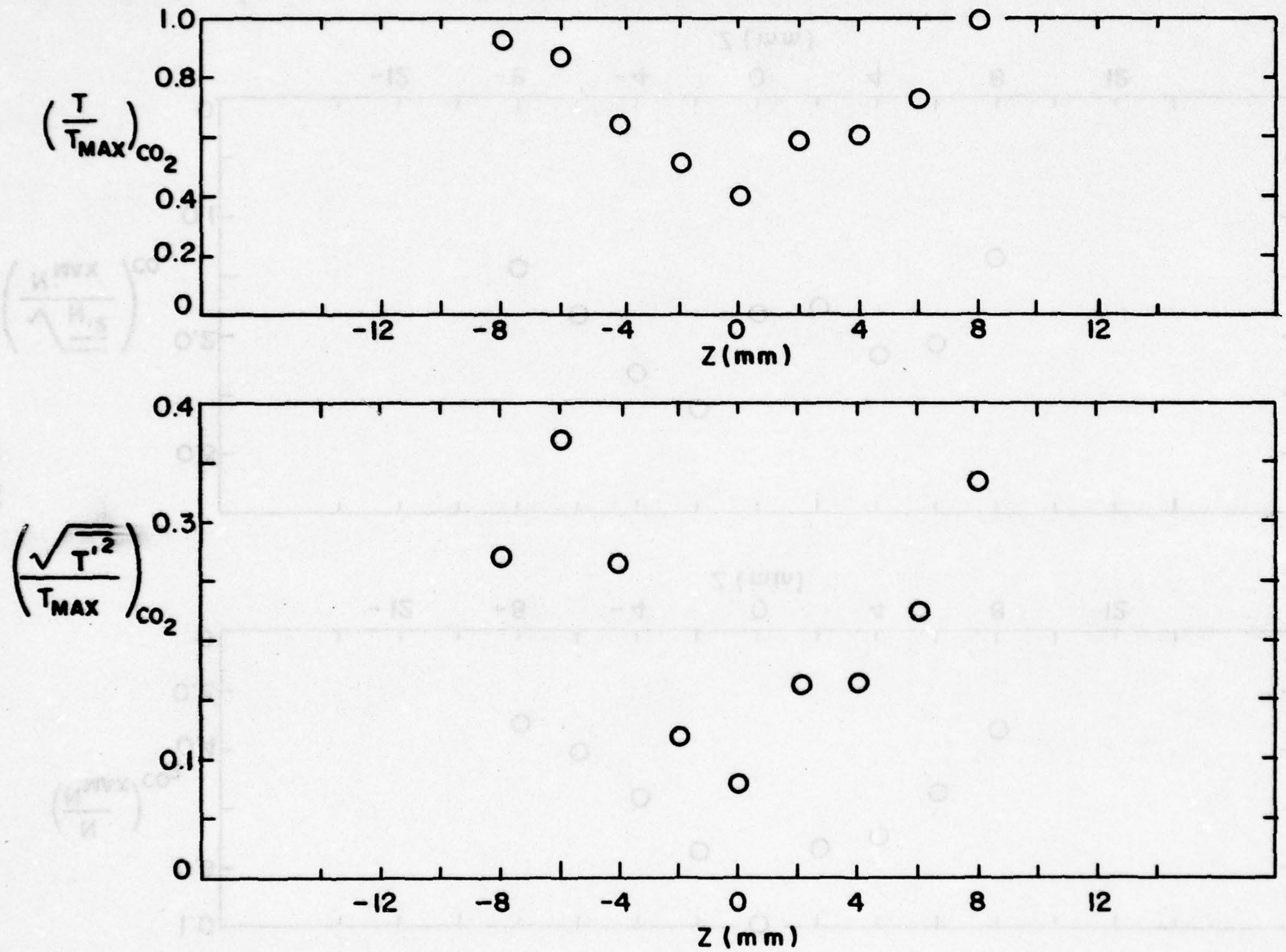


FIG. 23 CO_2 TEMPERATURE FLAME PROFILE AT X/D = 6.5

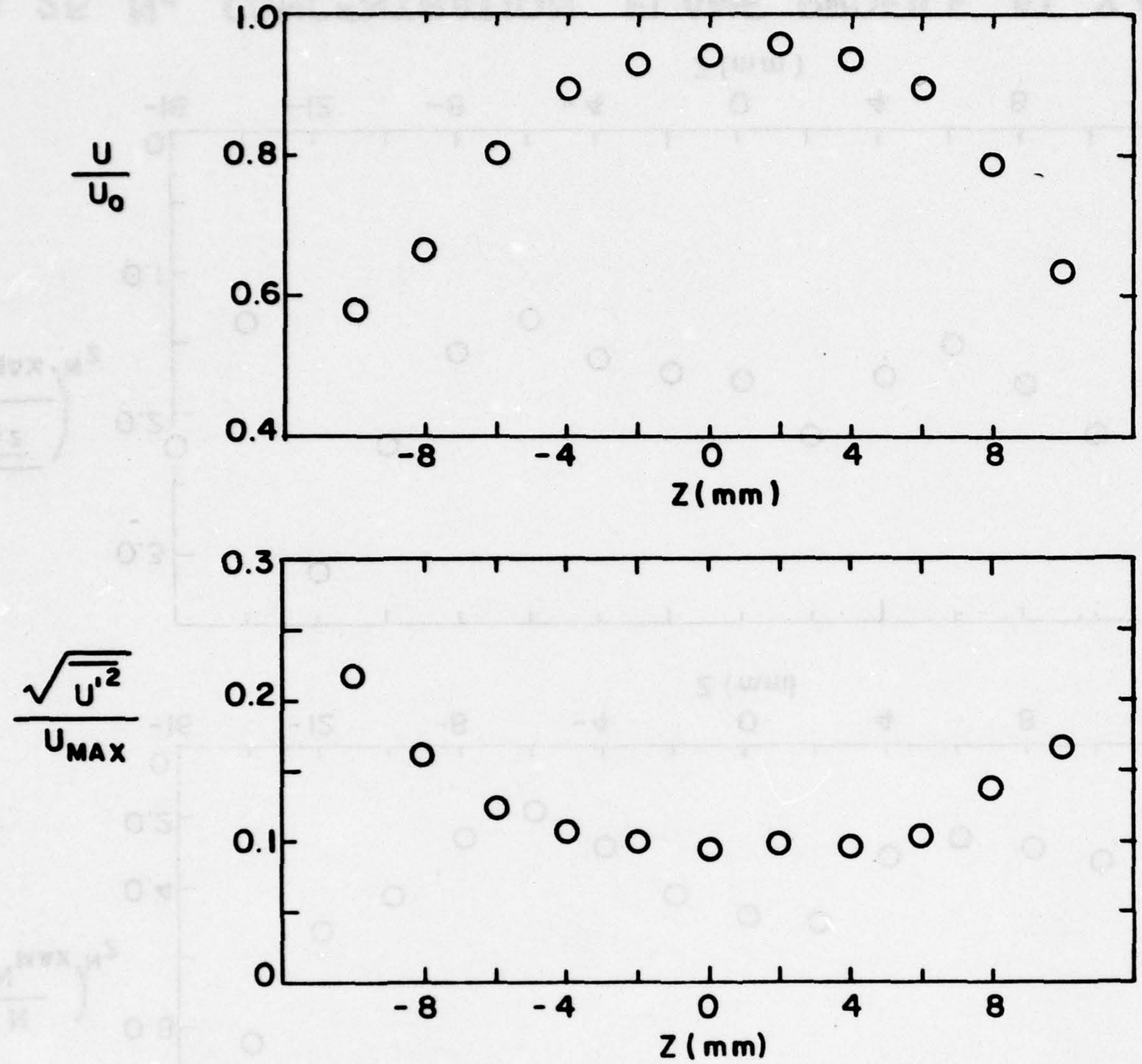


FIG. 24 FLAME RADIAL VELOCITY PROFILE AT X/D = 7.1, U_0 = 44.99 FT/SEC

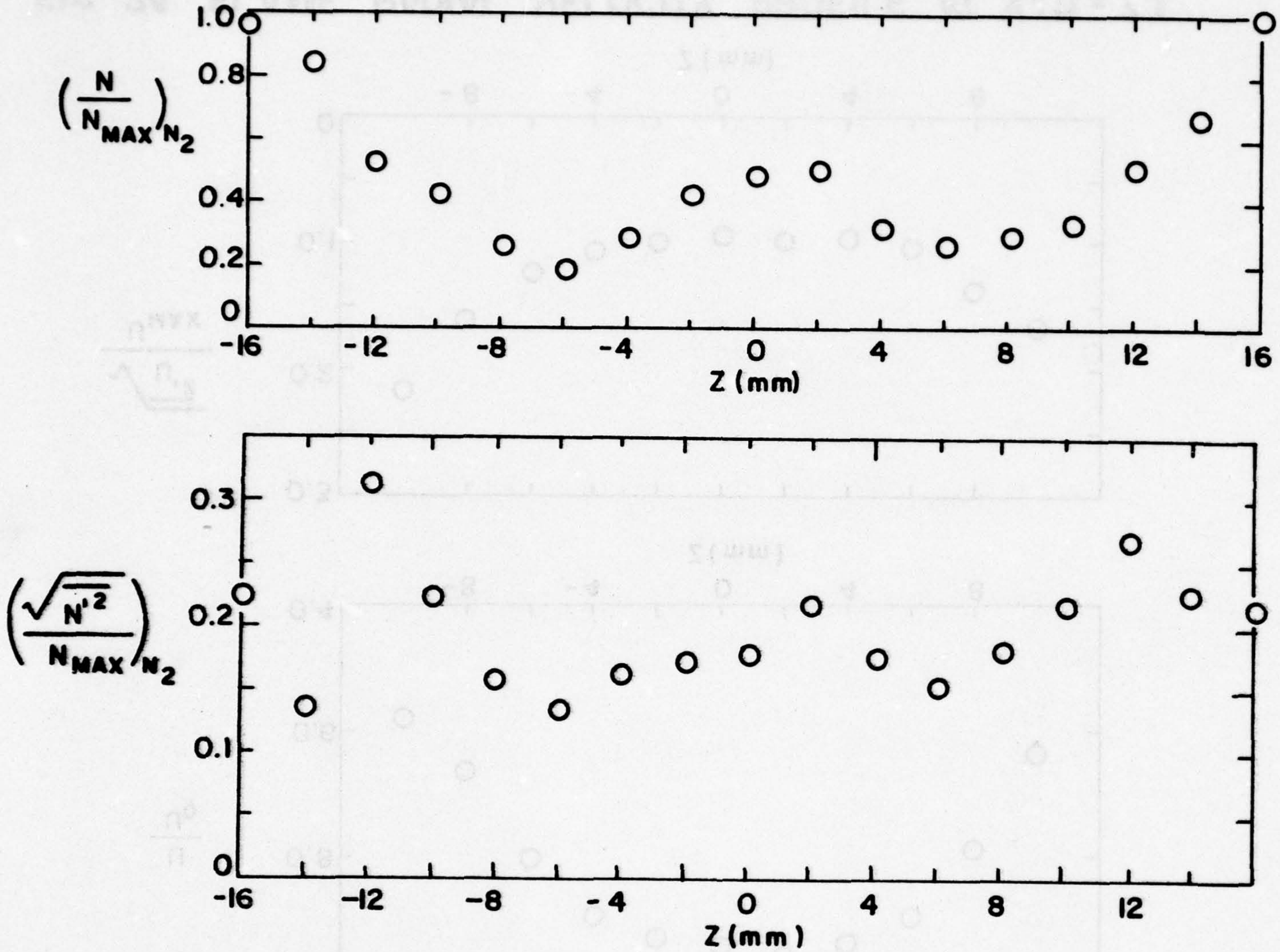


FIG. 25 N_2 CONCENTRATION FLAME PROFILE AT X/D = 7.1

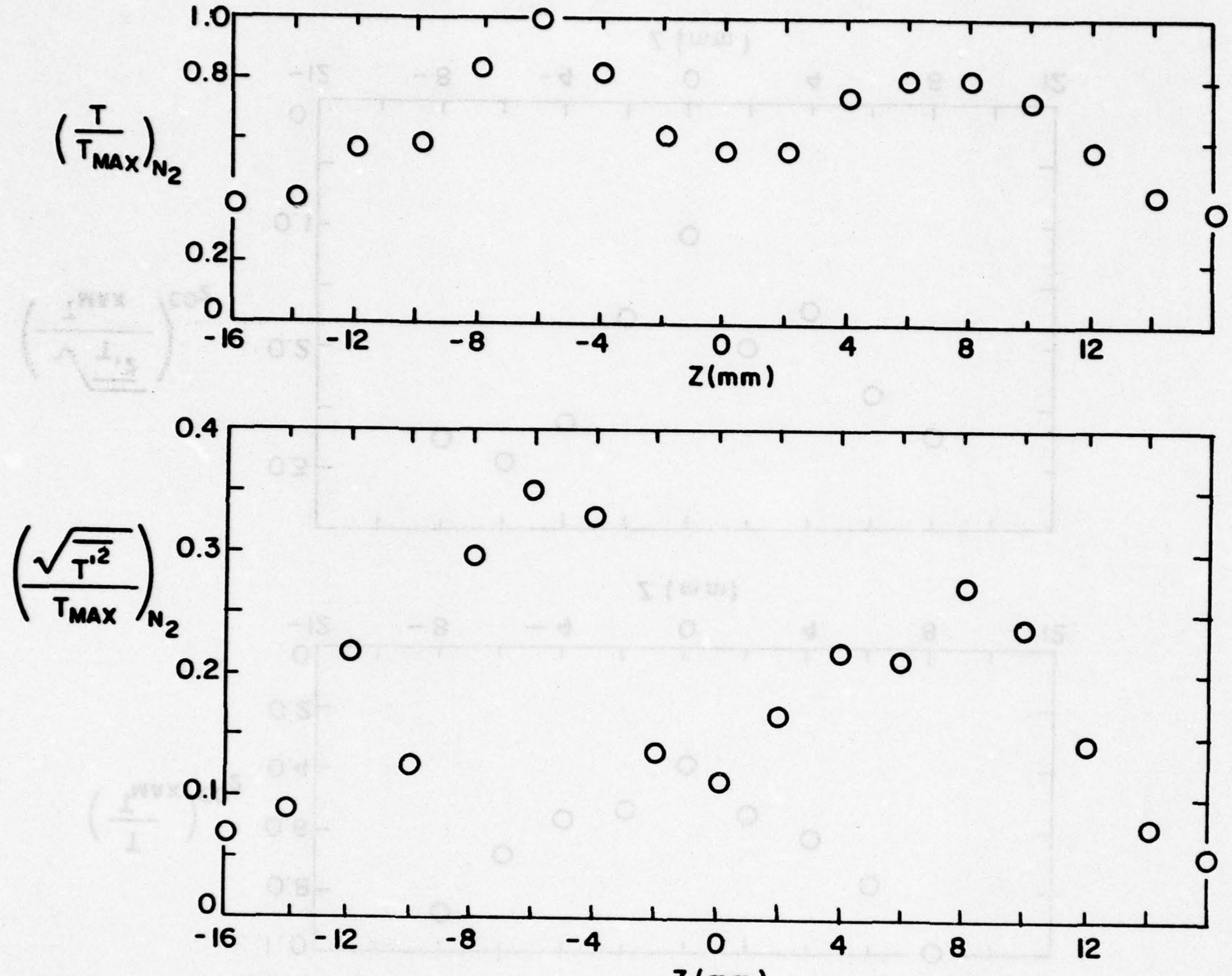


FIG. 26 N_2 TEMPERATURE FLAME PROFILE AT X/D = 7.1

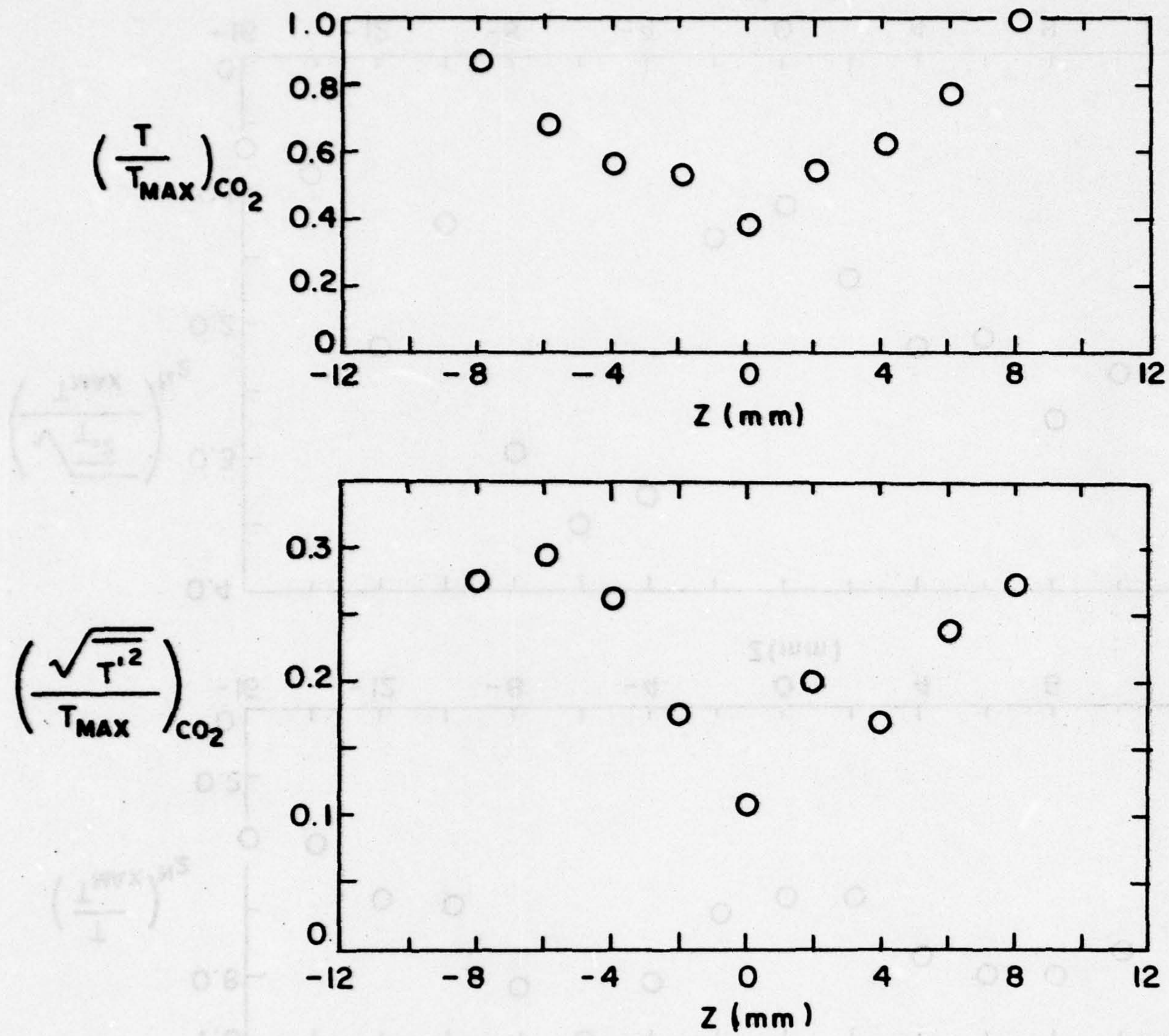


FIG. 27 CO_2 TEMPERATURE FLAME PROFILE AT X/D = 7.1

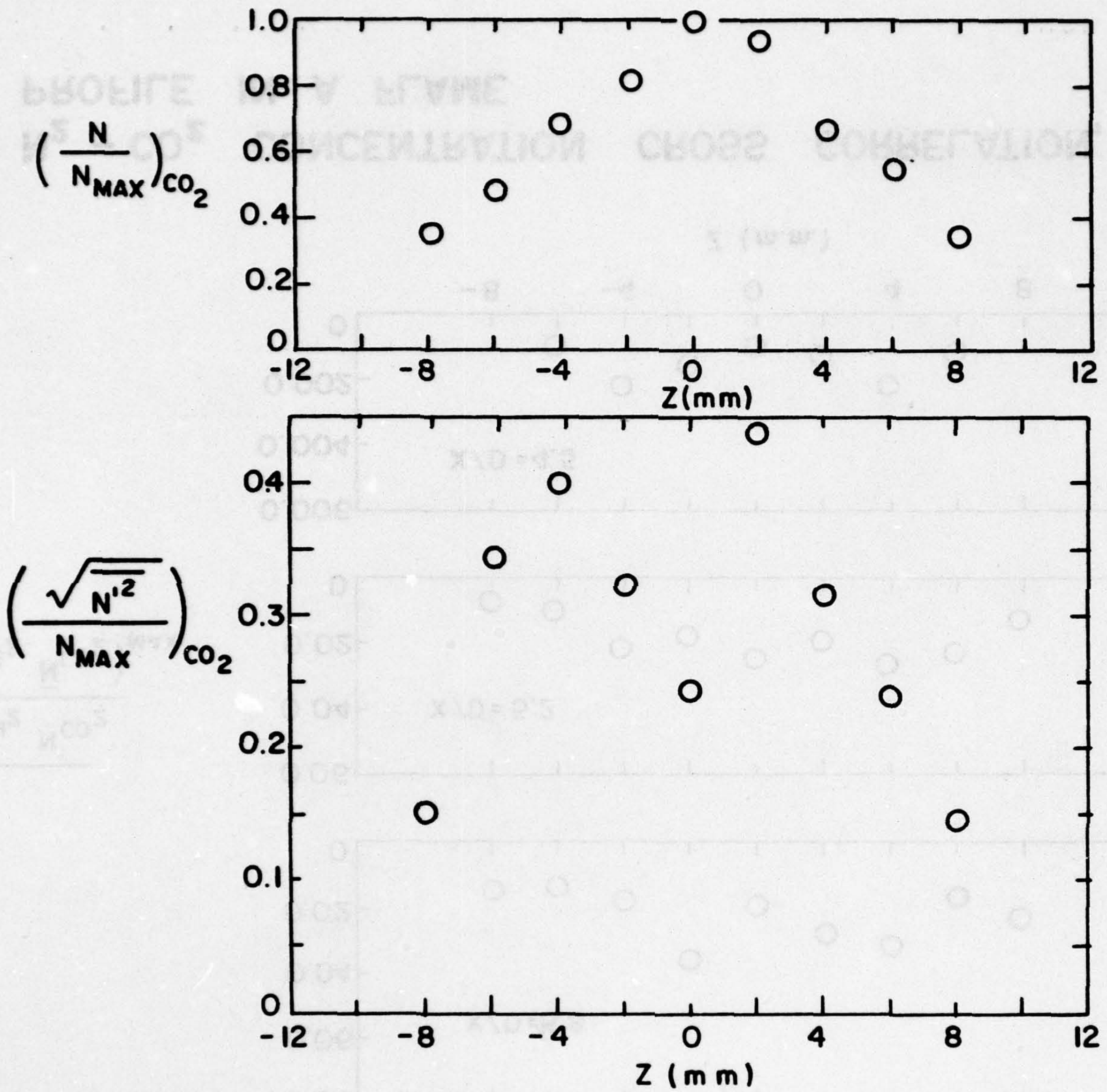


FIG. 28 CO_2 CONCENTRATION FLAME PROFILE AT X/D = 7.1

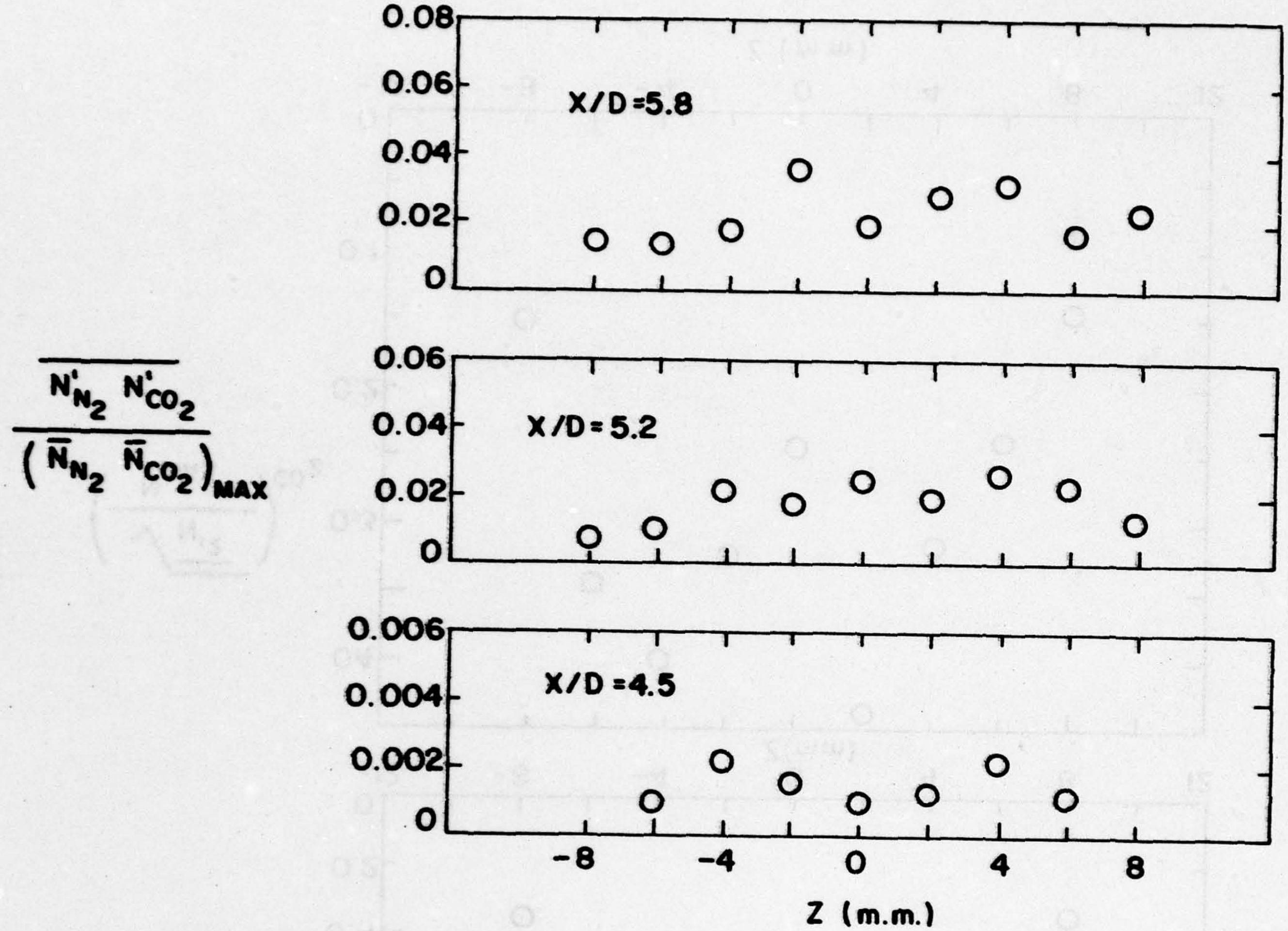


FIG. 29 N_2 - CO_2 CONCENTRATION CROSS CORRELATION, RADIAL PROFILE IN A FLAME

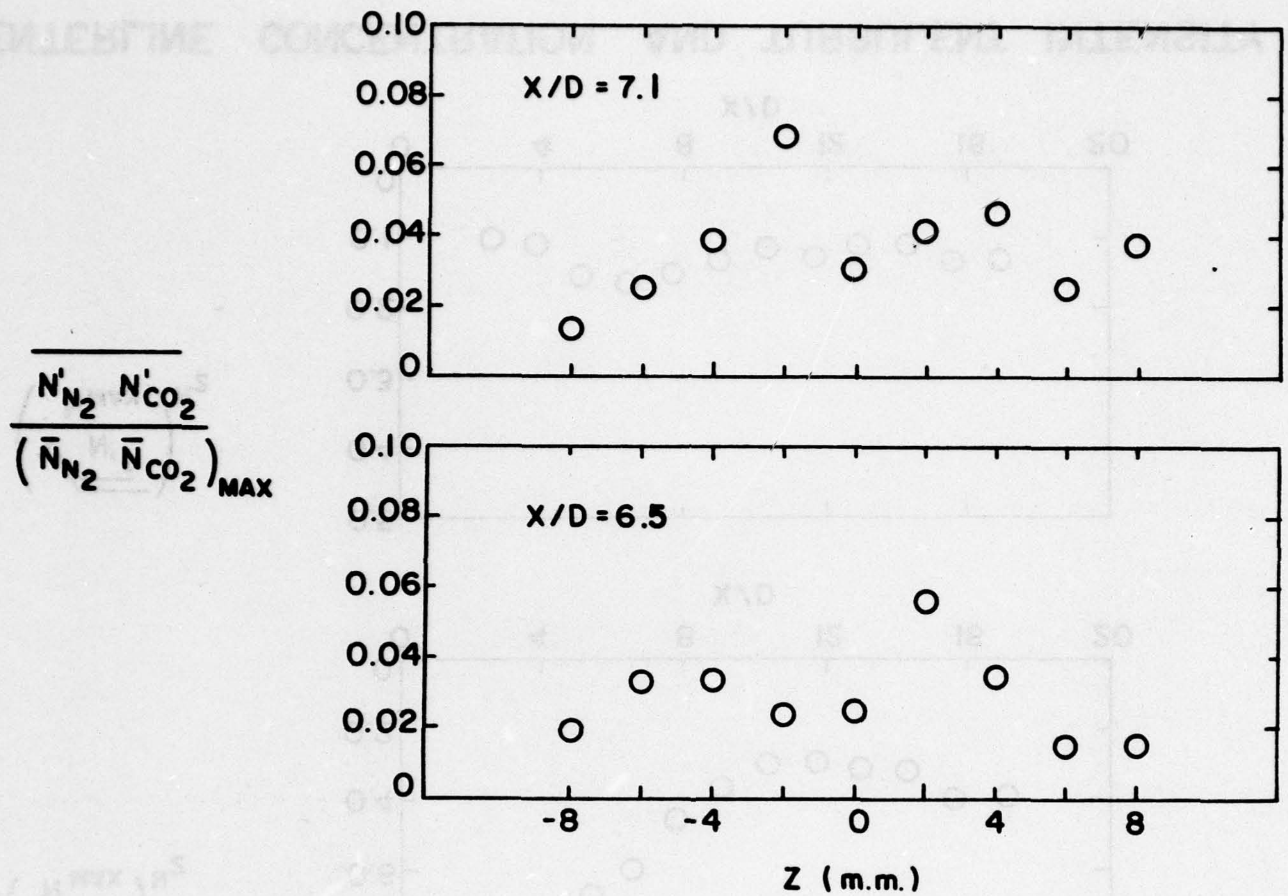


FIG. 30 $N_2 - CO_2$ CONCENTRATION CROSS CORRELATION, RADIAL PROFILE IN A FLAME

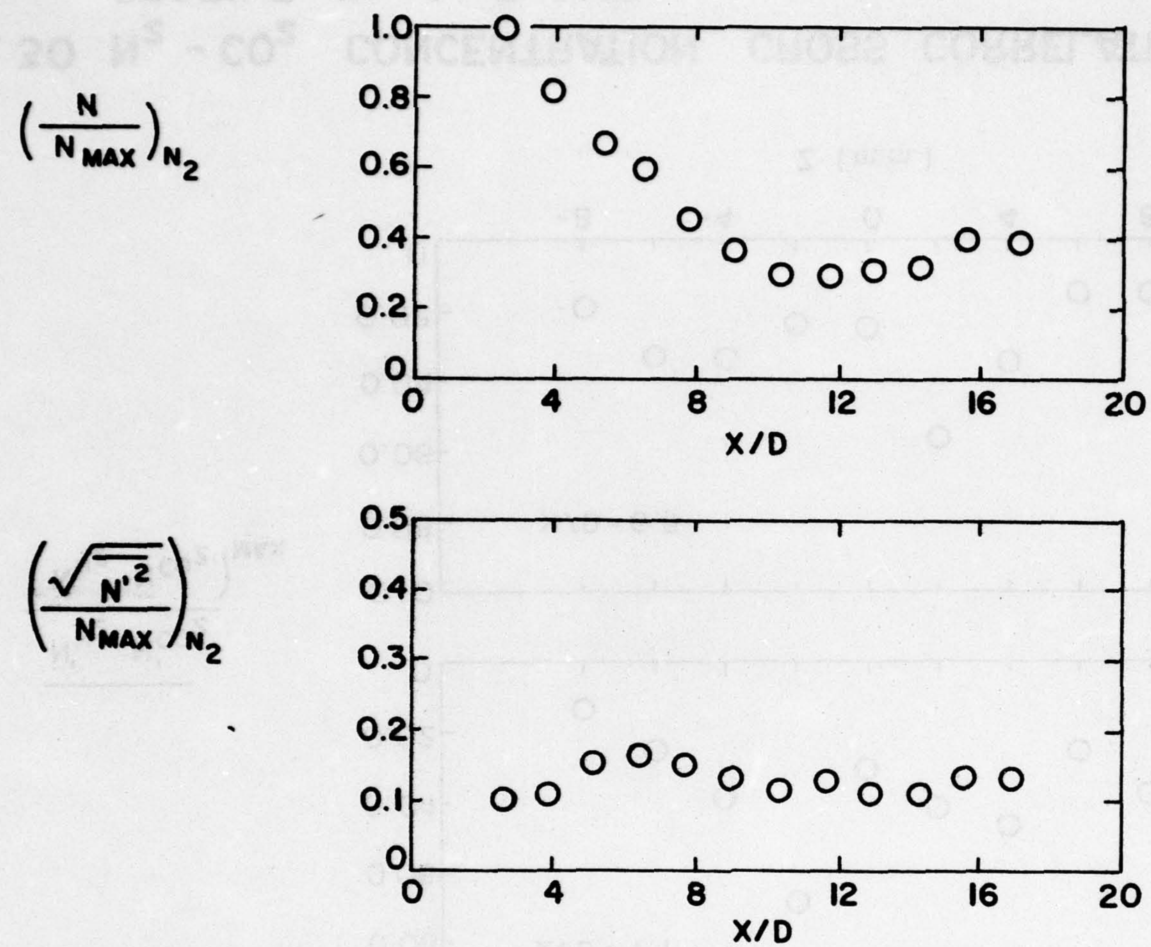


FIG. 31 CENTERLINE CONCENTRATION AND TURBULENT INTENSITY OF N_2

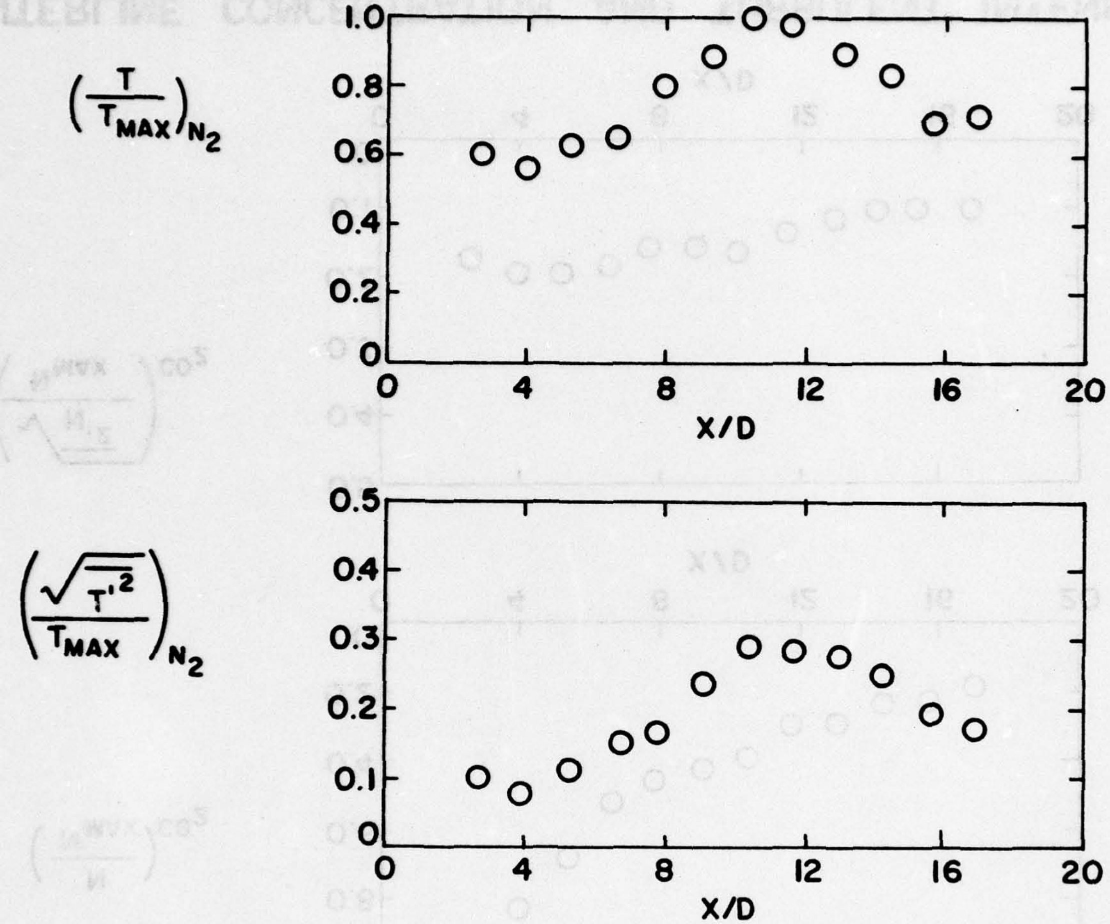


FIG. 32 CENTERLINE TEMPERATURE AND TEMPERATURE FLUCTUATION OF N_2

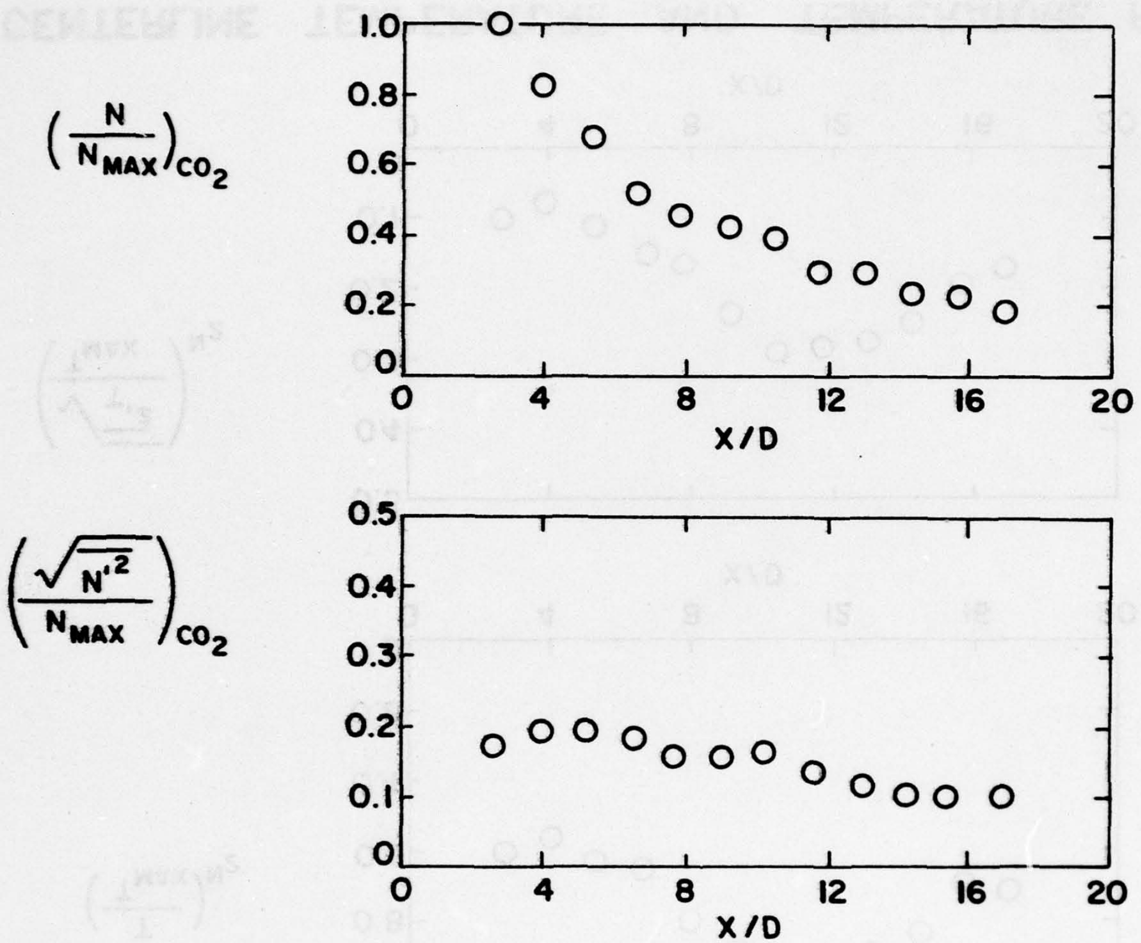


FIG. 33 CENTERLINE CONCENTRATION AND TURBULENT INTENSITY OF CO_2

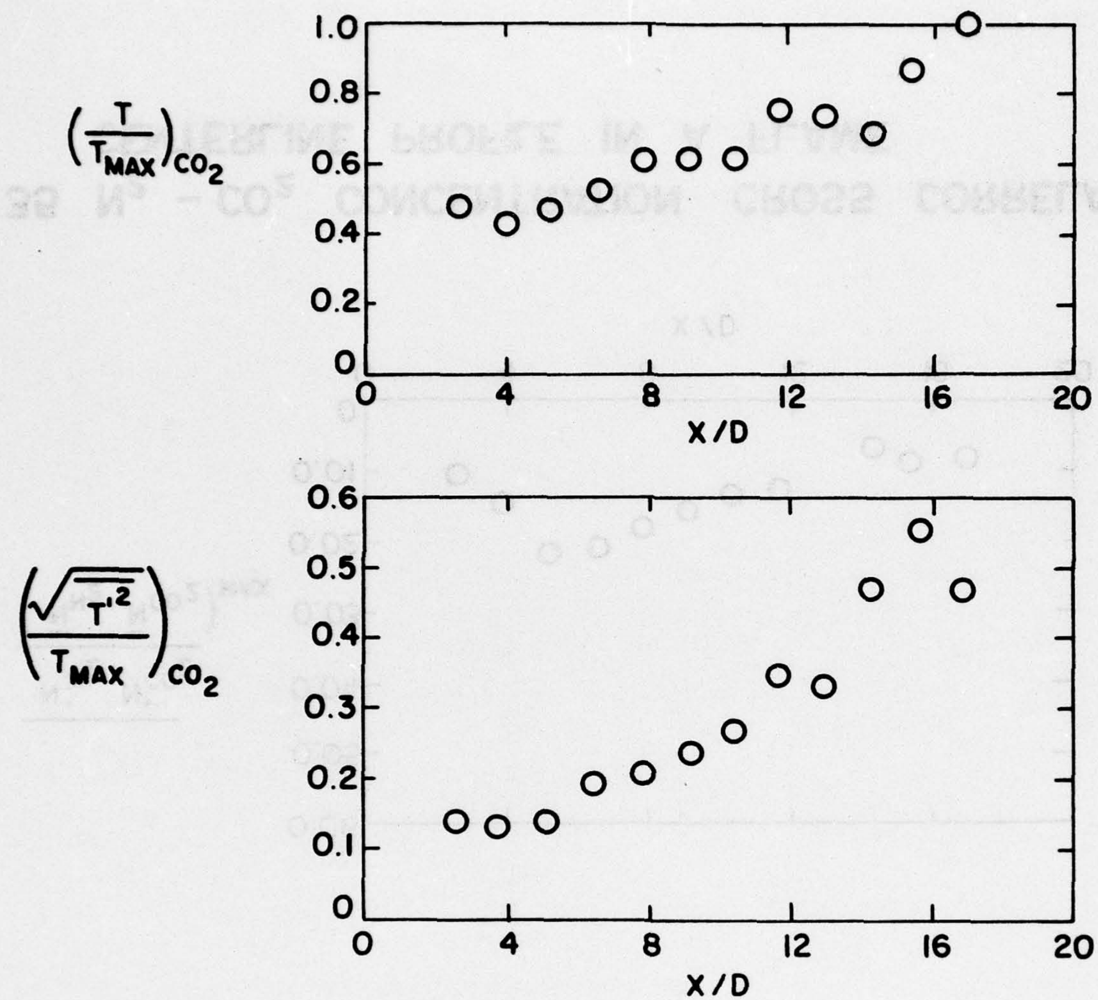


FIG.34 CENTERLINE TEMPERATURE AND TEMPERATURE FLUCTUATION OF CO_2

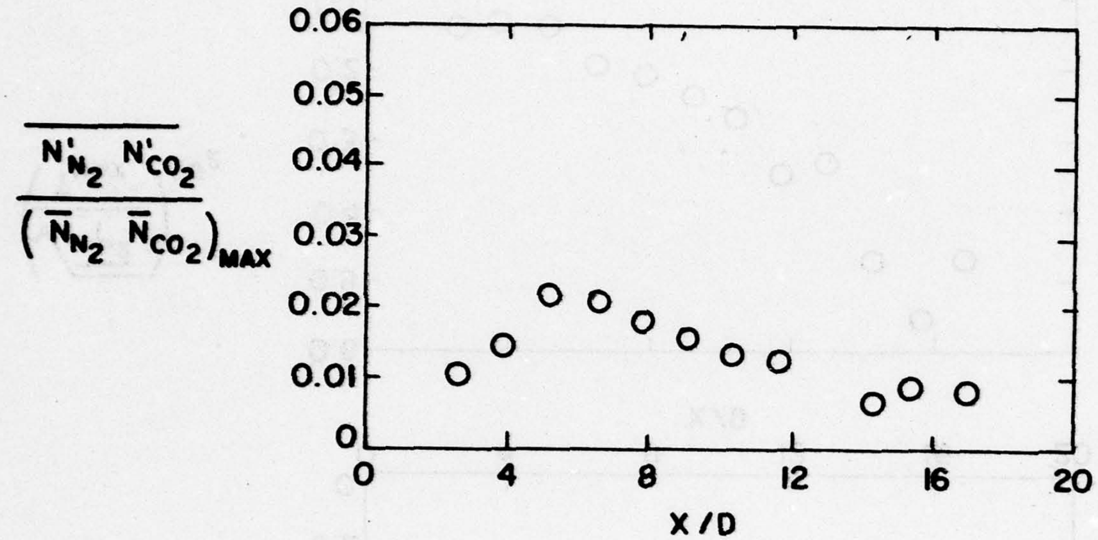


FIG. 35 $N_2 - CO_2$ CONCENTRATION CROSS CORRELATION, CENTERLINE PROFILE IN A FLAME

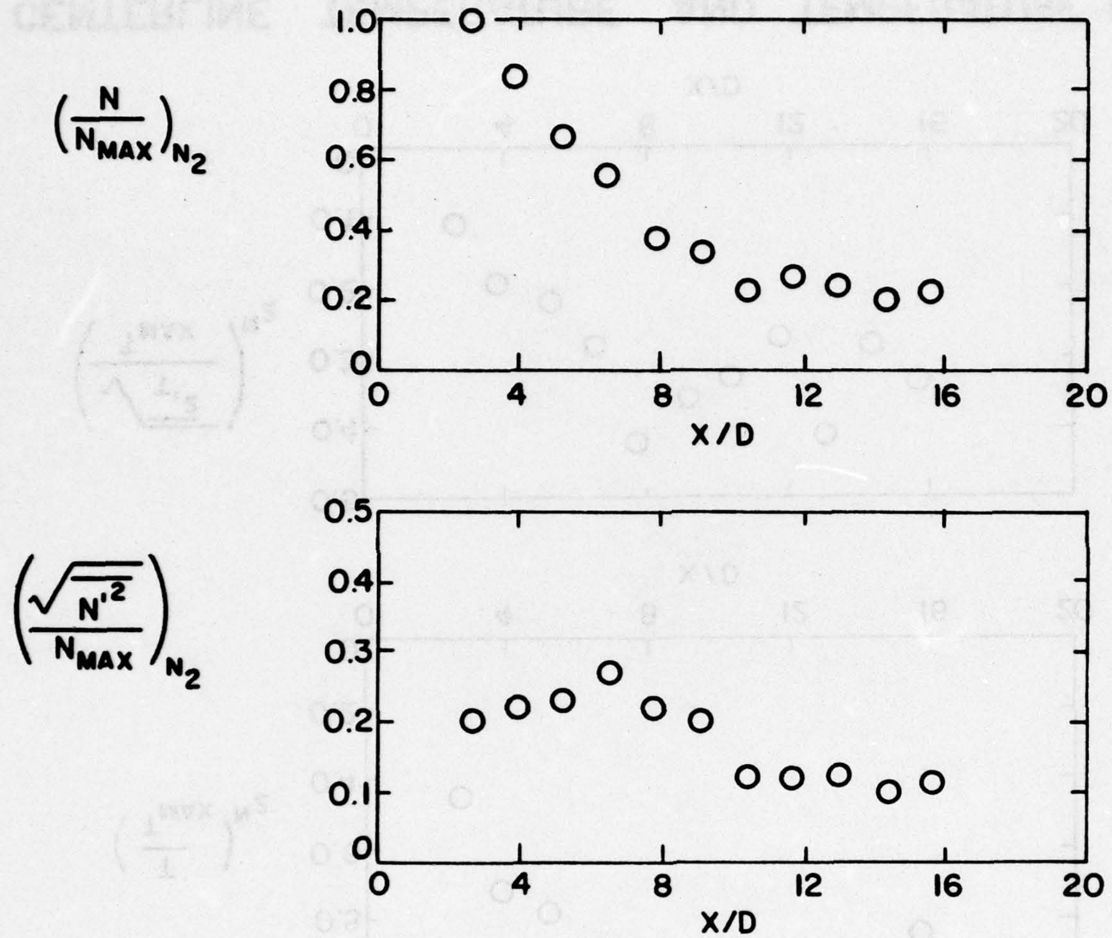


FIG.36 CENTERLINE CONCENTRATION AND TURBULENT INTENSITY OF N_2 IN THE PRESENCE OF CARBON PARTICLES

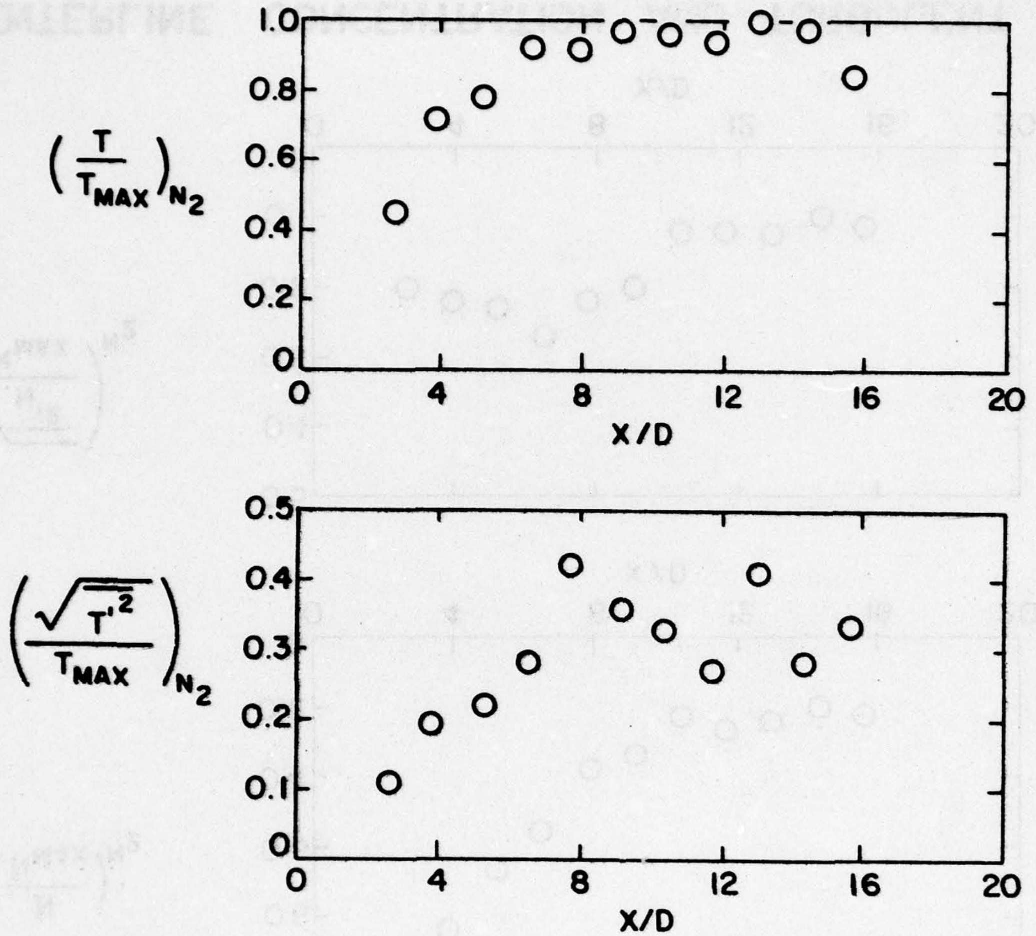


FIG. 37 CENTERLINE TEMPERATURE AND TEMPERATURE FLUCTUATION OF N_2 IN THE PRESENCE OF CARBON PARTICLES

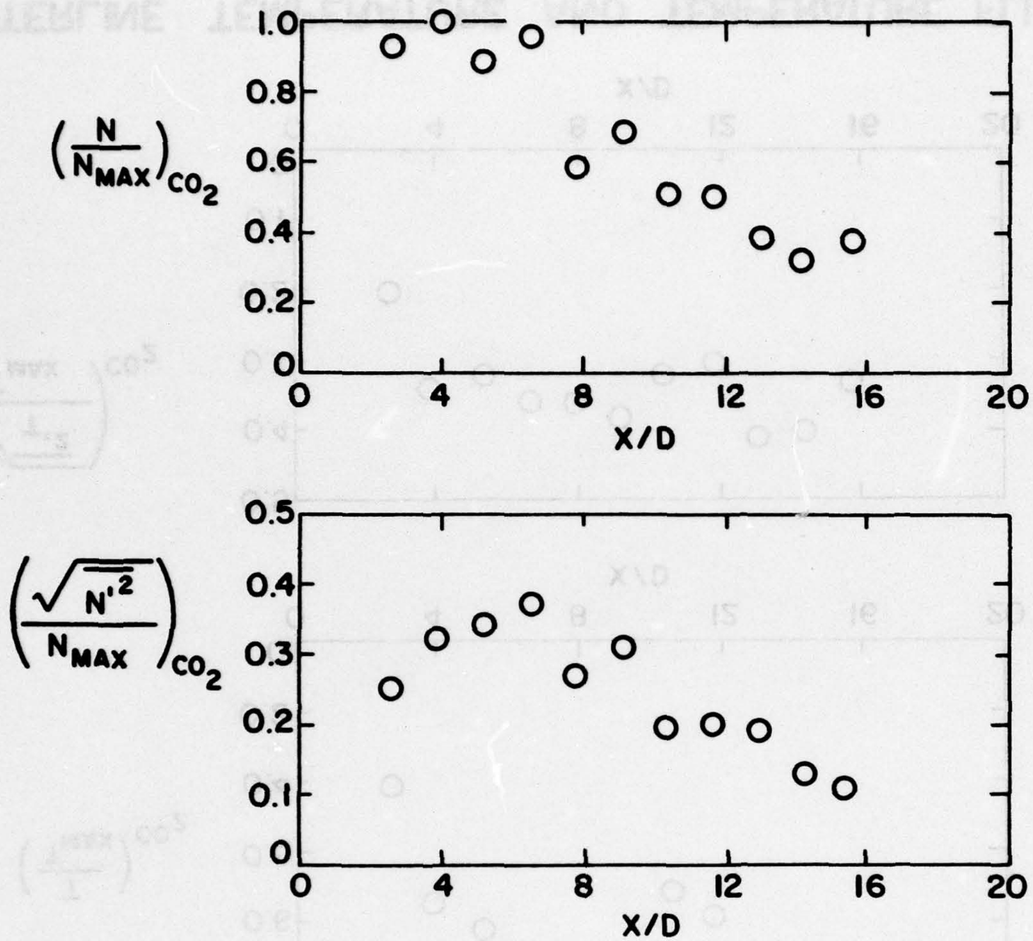


FIG.38 CENTERLINE CONCENTRATION AND TURBULENT INTENSITY OF CO_2 IN THE PRESENCE OF CARBON PARTICLES

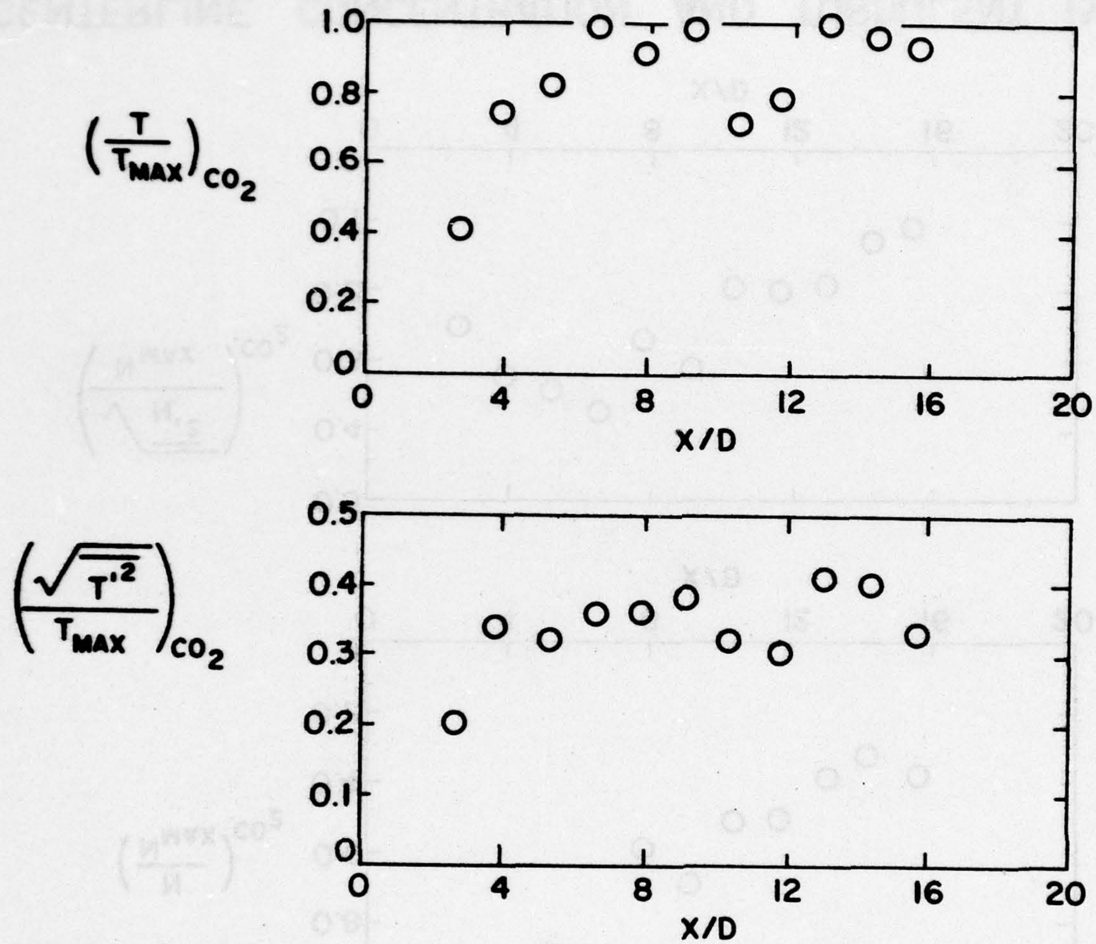


FIG.39 CENTERLINE TEMPERATURE AND TEMPERATURE FLUCTUATION OF CO_2 IN THE PRESENCE OF CARBON PARTICLES

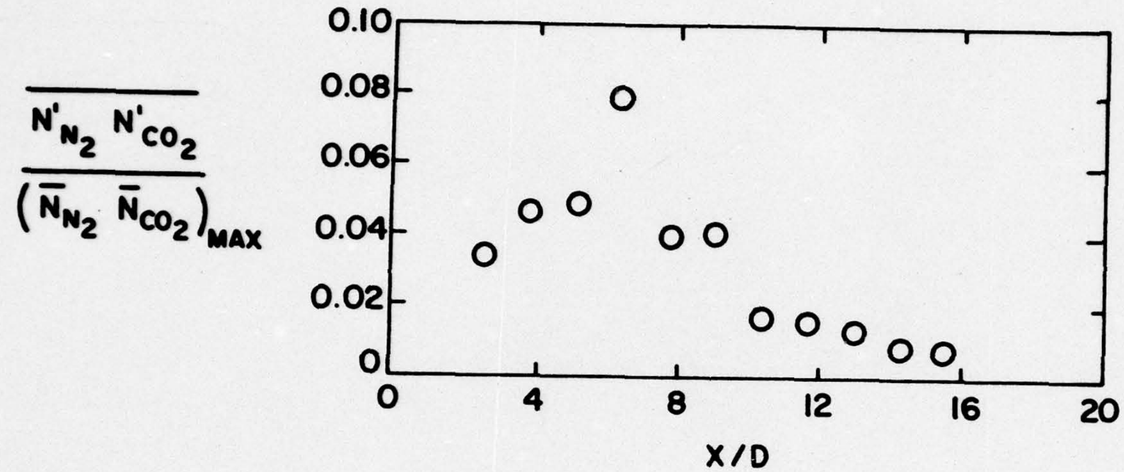


FIG. 40 $N_2 - CO_2$ CONCENTRATION CROSS CORRELATION, CENTERLINE PROFILE IN A FLAME WITH CARBON PARTICLES

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* (Laser Doppler Velocimeter)

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Raman	Turbulence
Doppler	Flame
Concentration	Jet
Temperature	Correlation parameters
Velocity	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A series of test results concerning a coaxial jet and coaxial turbulent diffusion methane flame are presented. It is shown that the integrated LDV(*) and pulsed Raman technique represent one of the most complete diagnostic systems available. It is capable of providing, velocity, turbulence intensity, concentration of species, temperature, concentration and temperature fluctuation, as well as the correlation parameters for chemically reacting turbulent phenomena. All of the above can be obtained simultane-

→ next page

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20. Abstract (Continued)

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